SECTION 5. CHESAPEAKE BAY MONITORING AND MODELING FRAMEWORKS

For purposes of developing the Chesapeake Bay TMDL, data and scenario results from extensive monitoring networks and a series of linked environmental models simulating the nutrient and sediment pollutant load sources and the associated water quality and biological responses have been applied to support decision making by EPA and its partner Bay watershed jurisdictions. The suite of models was developed, calibrated and verified using long-term Bay, watershed, airshed, and land-cover monitoring observations and published technical and scientific findings.

The suite of monitoring and modeling frameworks provide accurate and reliable representation of the complex Bay water quality processes. The models are valuable tools in synthesizing an enormous amount of data, predicting outcomes, providing allocation scenarios and tracking progress toward restoration of the Bay. Models have some inherent uncertainty. Because of the amount of data and resources taken to develop, calibrate, and verify the accuracy of the Bay models, the uncertainly of the suite of models is minimized.

5.1 Technical Monitoring and Modeling Requirements

The combined Chesapeake Bay monitoring and modeling frameworks effectively address all the factors necessary for developing a scientifically sound and reliable TMDL that meets the TMDL regulatory requirements. The factors addressed in and through the various models are the following:

- Regulated point sources and non-regulated nonpoint sources of nitrogen, phosphorus, and sediment are fully considered and evaluated separately in terms of their relative contributions to water quality impairment of the Chesapeake Bay's tidal waters.
- Water quality impairments in the Bay are temporally and spatially variable and are directly limited to nutrient and sediment pollutant loadings.
- Time-variable aspects of land practices that have a large effect on nutrient and sediment loadings and resulting water quality in the Bay are fully simulated.
- All sources of data are gathered using methodologies fully consistent across the Bay watershed helping ensure equitable allocation of the resultant load reduction responsibility across the seven watershed jurisdictions and multiple pollutant source sectors.
- The modeling framework takes advantage of decades of atmospheric deposition, streamflow, precipitation, water quality, biological resource and land cover monitoring data generated through the Bay-wide tidal and basinwide watershed monitoring networks as well as tracking and reporting of the implementation of pollution load reduction practices and technologies for model calibration and verification.
- A wide variety of hydrological conditions have been characterized through decades of monitoring to provide reliable simulations in support of management decision making across the decadal-scale model hydrologic periods.
- The combined monitoring and modeling frameworks provide the ability to simulate and assess the critical spatial and temporal variability of the Bay water quality criteria—DO,

water clarity, underwater Bay grass acreage, and chlorophyll *a*—as adopted into the jurisdictions' WQS regulations.

The primary regulatory factor that must be addressed by the combined monitoring and modeling frameworks is whether the TMDL allocation scenario will attain and maintain the applicable WQS. To make that assessment, the models must be able to relate the pollutant loading from all sources to achievement of the Bay jurisdictions' Chesapeake Bay WQS across all tidal waters. A determination that a particular scenario achieves compliance with the applicable water quality criteria within each segment for each of the jurisdictions' WQS requires evaluating the water quality impacts of pollutant loadings on multiple parameters across all seasons over a minimum of 3 years (USEPA 2003a, 2007a). As a result, the models must provide a time-variable analysis. In addition, the modeling framework should also be useful in developing and evaluating action plans for implementation, and confirming those combined implementation actions will yield achievement of Chesapeake Bay WQS (USEPA 2008b, 2009c, 2010d).

5.2 Bay Monitoring Framework Overview

In August 1984, the original Chesapeake Bay tidal monitoring program was created to achieve three objectives: characterize the baseline water quality conditions; detect trends in water quality indicators; and increase the understanding of ecosystem process and factors affecting Bay water quality and living resources (MD OEP 1987). The long-term Chesapeake Bay and watershed monitoring networks have accomplished many more objectives in the past 26 years, including the following:

- Classifying status and tracking trends in water quality and living resources response to management actions
- Supporting a scientific basis for targeting a dual nutrient strategy to water quality and habitat health recovery
- Identifying eutrophication as the primary cause of SAV decline
- Providing sufficient and diverse data supporting scientifically based and peer-reviewed estuarine water quality criteria development to guide restoration targeting and water quality assessments (e.g., CWA section 303(d) listing/delisting decisions)
- Supporting decision makers' needs for the Bay TMDL process with high-quality data underlying Chesapeake Bay water quality model development, calibration and verification

5.2.1 Partnership's Chesapeake Bay Tidal Monitoring Network

Undergoing adaptive changes over the almost three decades as management needs and requests have significantly evolved over time (CBP 1989a, 1989b; USEPA 2003a; MRAT 2009), the Chesapeake Bay tidal monitoring network includes the following:

- Tidal water quality monitoring for 26 parameters at over 150 stations distributed over the 92 Chesapeake Bay tidal segments
- Shallow-water monitoring addressing a select set of segments on a rotational basis
- Benthic infaunal community monitoring at fixed and random stations across the tidal waters
- Annual aerial and ground surveys of underwater Bay grasses

Each component of the tidal monitoring network has been designed to support the Bay jurisdictions' tidal water Bay section 303(d) listing decision makings, addressing DO, water clarity, SAV, and chlorophyll *a* criteria attainment assessments and benthic infaunal community-based impairment decisions (USEPA 2003a, 2004a, 2007a, 2007b, 2008a, 2010a).

The Bay tidal monitoring network is funded, operated, and maintained through a longstanding state-federal-university partnership that produces fundamental data supporting Bay TMDL development. This data is utilized in public reporting on the health of the Bay, its tidal rivers, and supporting ecosystem; assessment of achieving the Bay jurisdictions' Chesapeake Bay WQS regulations; evaluation of the effectiveness of actions to reduce nutrient and sediment pollution from the surrounding watershed; developing, calibrating, and verifying models; and generating water quality and living resource indicators.

Chesapeake Bay Water Quality Monitoring

The long-term Chesapeake Bay water quality monitoring program uses a fixed station strategy with sites distributed along the mid-channel waters of the Bay and its tidal tributaries and embayments. The exact number of stations has varied over the 26-year history of the program. A set of 162 stations that have been sampled consistently for the majority of those years is illustrated in Figure 5-1. One or more stations are in each of the 92 Bay segments. Over the 26-year history of the program, sampling frequency has ranged from 20 times per year to the present 14 cruises annually. Synoptic sampling of all the tidal waters takes 1–2 weeks with available resources.

At each station, vertical profiles of in-situ water quality measurements are made using instrumentation and standard operating procedures approved by the Chesapeake Bay Program's Analytical and Methods Workgroup (see Section 5.2.3). Measurements are collected at 0.5 m, 1.0 m, 2.0 m and 3.0 m and at a maximum of 2-meter intervals from 1.0 m below the surface to 1.0 m above the bottom. Water temperature, DO, conductivity, and pH are recorded at each depth. Photosynthetic Active Radiation measurements are made, and Secchi depth measurements are recorded using a Secchi disc.

At stations where stratification provides a pycnocline, grab samples are collected at 0.5 m below the surface, at 1.5 m above the upper pycnocline, at 1.5 m below the lower pycnocline and at 1.0 m above the bottom. At stations with no identifiable pycnocline as determined by the protocol, grab samples are collected at 0.5 m below the surface and 1.0 m above the bottom, and at the physical profiling depths which are above one-third and two-thirds the distance between the surface- and bottom-sampling depths. Each of the grab sample depths again corresponds to an in-situ water quality measured profiling depth.

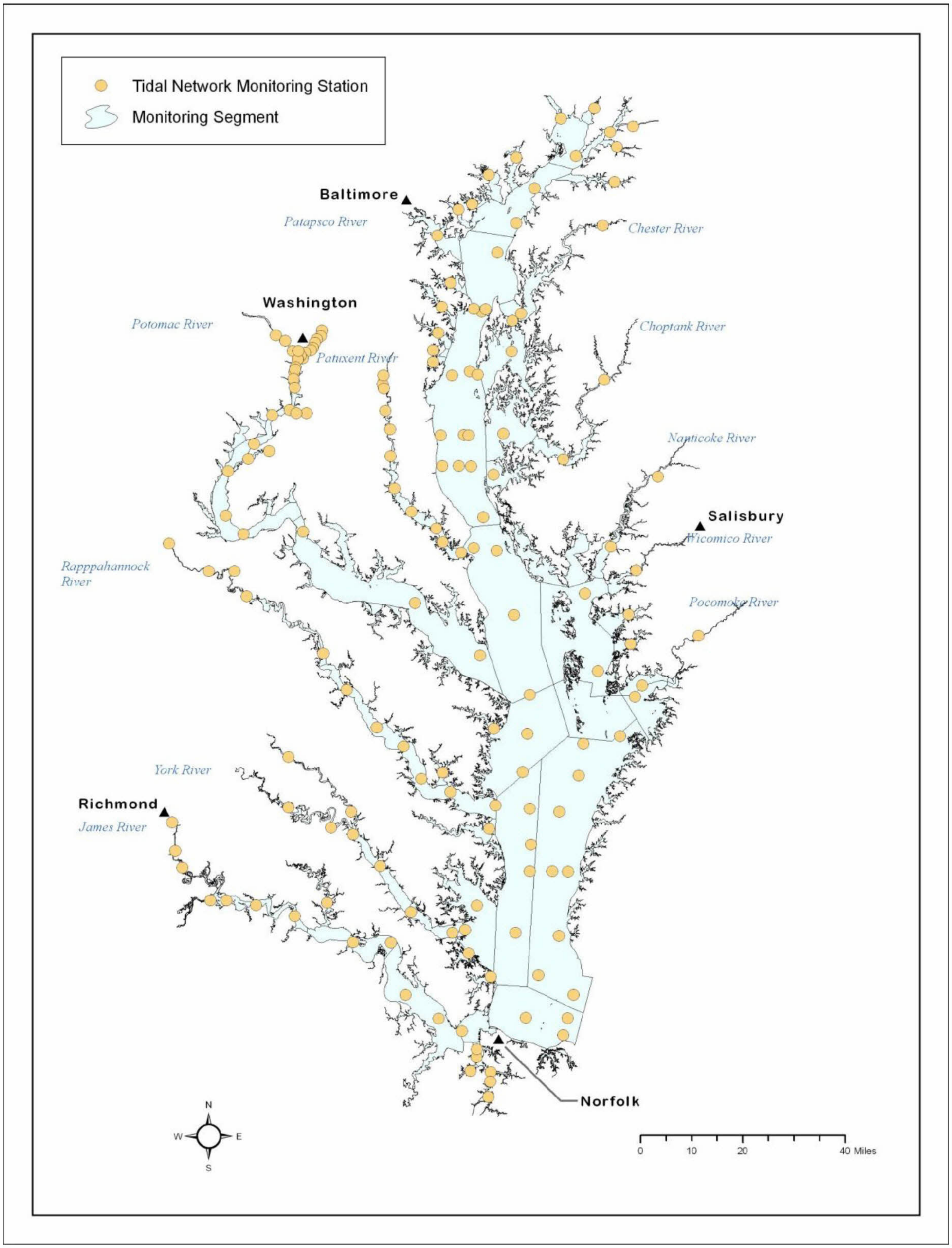


Figure 5-1. Tidal monitoring network stations.

Shallow-Water Monitoring

For shallow water habitat, monitoring consists of high-speed, spatially detailed water quality mapping (data collected every 4 seconds) called DATAFLOW, and high-frequency (15-minute measurement intervals) continuous monitoring at fixed sites (CONMON) (USEPA 2007a). The high-resolution measurements record water temperature, DO concentration, DO saturation, pH, salinity (derived from conductivity), turbidity, and fluorescence (used to estimate chlorophyll *a*).

CONMON measurements are collected March to November. All sondes (i.e. data measurement devices) are either at constant depth of approximately 1 m below the surface or at a fixed depth from the bottom (0.3 m–0.5 m) depending on depth conditions. In addition to the suite of measurements collected by the CONMON meter, LI-COR sensors measure the light penetration at the site on each visit. A Secchi measurement is also collected. As a part of standardized operating procedures to ensure data quality, each CONMON site is serviced biweekly unless water quality readings demonstrate that weekly intervals should be maintained. During each site visit, instruments in the water are calibrated against replacement instruments and a third instrument. Discrete grab water samples are collected for chlorophyll *a*, turbidity, and TSS calibration. A nutrient suite is further conducted on the discrete water sample. Upon swapping out instruments, the instrument removed from the field is returned to the lab for cleaning and lab calibration before being redeployed.

DATAFLOW is conducted on a subset of Bay segments each year with monthly measurements from April to October. Measurements are made while traveling in a boat at speeds up to 25 knots. The DATAFLOW system is compact, can fit on a small boat, and allows sampling in shallow water with the ability to map an entire small tidal tributary in a day or less. This program complements the long term fixed station monitoring by providing data in nearshore shallow water habitats critical to SAV where water quality behaves differently from the mid-channel measures.

DATAFLOW calibration data are collected at multiple sites to either coordinate with long-term or CONMON monitoring stations, and large signal areas to insure coverage of the data gradient with the calibration. Discrete grab water samples are collected for chlorophyll. In addition, measurements of physical parameters and Secchi depth are made, and on PAR to calculate water column light attenuation (Kd). There is quality assurance/quality control (QA/QC) on the data set upon returning from the field.

To date, 65 of the 92 Chesapeake Bay segments have 1 to 3 years of shallow-water monitoring data available for assessment (Figure 5-2).

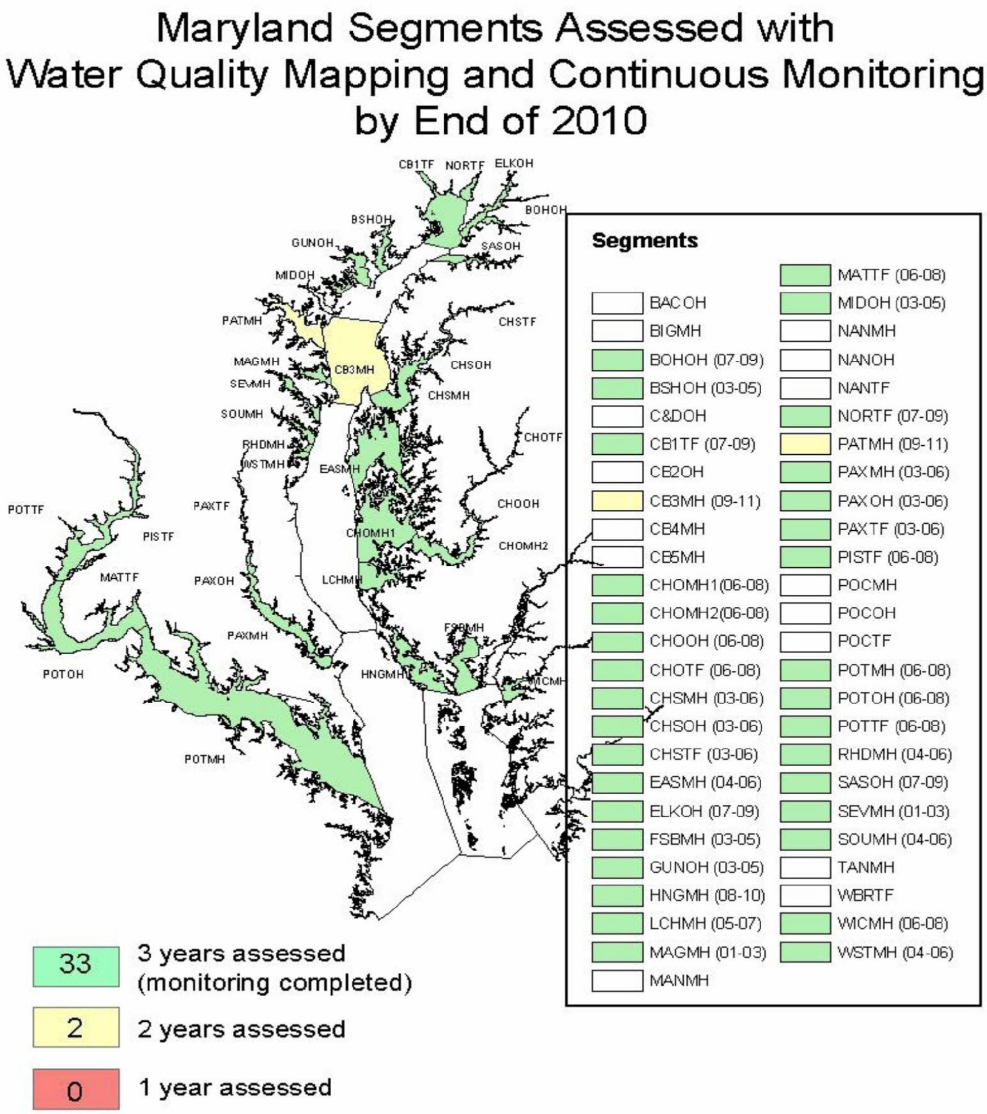
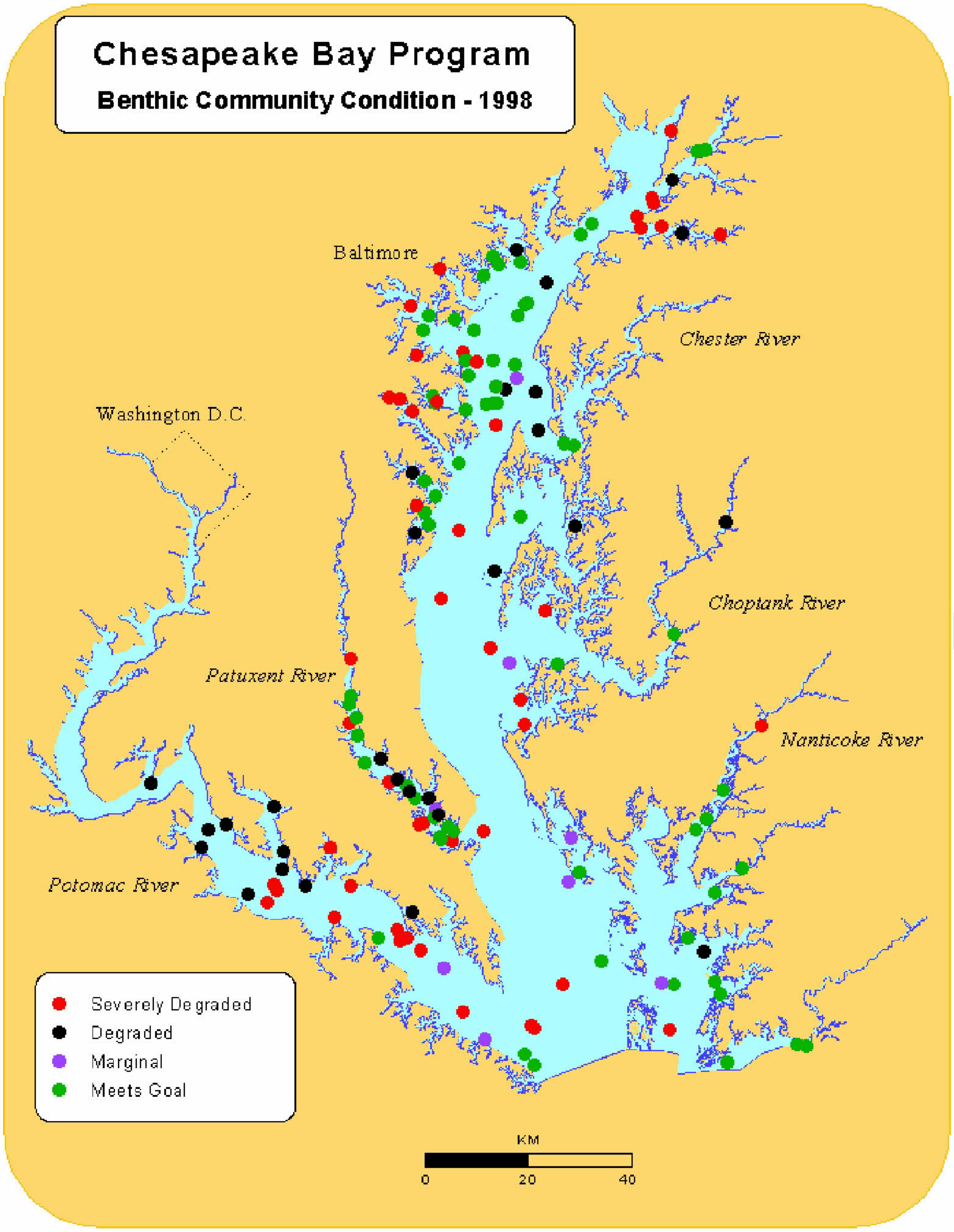


Figure 5-2. Shallow-water monitoring illustrating segment completion and latest rotation for Maryland.

Benthos

The current Bay-wide benthic monitoring program, initiated in Maryland in 1984 and in Virginia in 1985, now consists of fixed and random site components. The fixed site monitoring program has 53 stations traditionally sampled annually in spring and summer. All fixed sites in Maryland and Virginia are sampled using three replicate bottom grabs. The probability-based, random strata sampling was initiated in Maryland in 1994. Since 1996, the probability-based sampling program has become the standardized approach in Virginia as well, providing a Bay-wide regulatory assessment estimating impaired habitat conditions. The impairment assessment relies on approximately 200 sites sampled between July 15 and September 30 each year (Figure 5-3). Benthos are collected with a Young grab sampler at the probability-based sites.



Source: R. Llanso, VERSAR, Inc.

Figure 5-3. Example of results from the probability-based sampling distribution, 1998, to estimate habitat impairment through benthic community condition assessment.

Submerged Aquatic Vegetation

Consistent annual SAV aerial surveys commenced in 1984 and have been completed every year (except 1988) to the present providing detailed mapping of SAV bed coverage, acreage, estimated density, and, in combination with ground survey, species identification (Figure 5-4). In 2001 the program increased efficiency and accuracy by scanning aerial photography from digital negatives and orthorectifying (i.e. geometric correction of the photograph) the images using image processing software. SAV beds are categorized visually according to density on the basis of percent cover estimates. SAV beds are generally photographed May through October—lower Bay SAV in May and June, and low salinity and freshwater areas August through October.

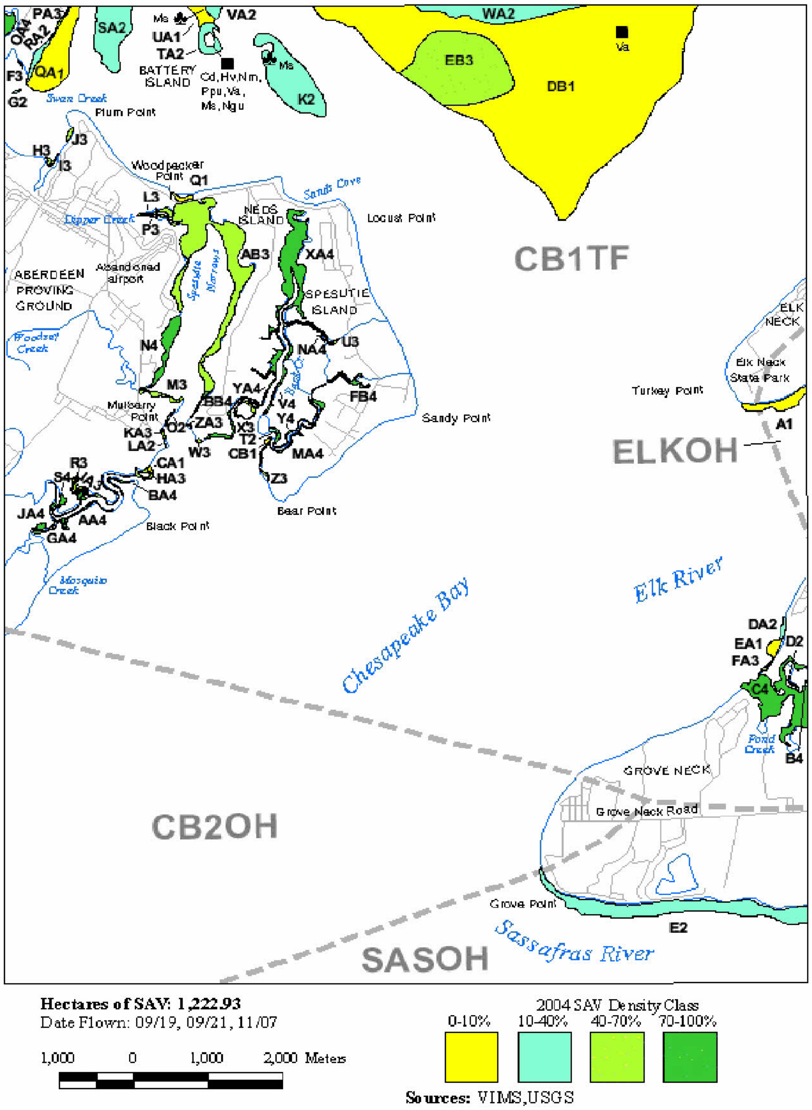


Figure 5-4. One way of illustrating SAV mapping results.

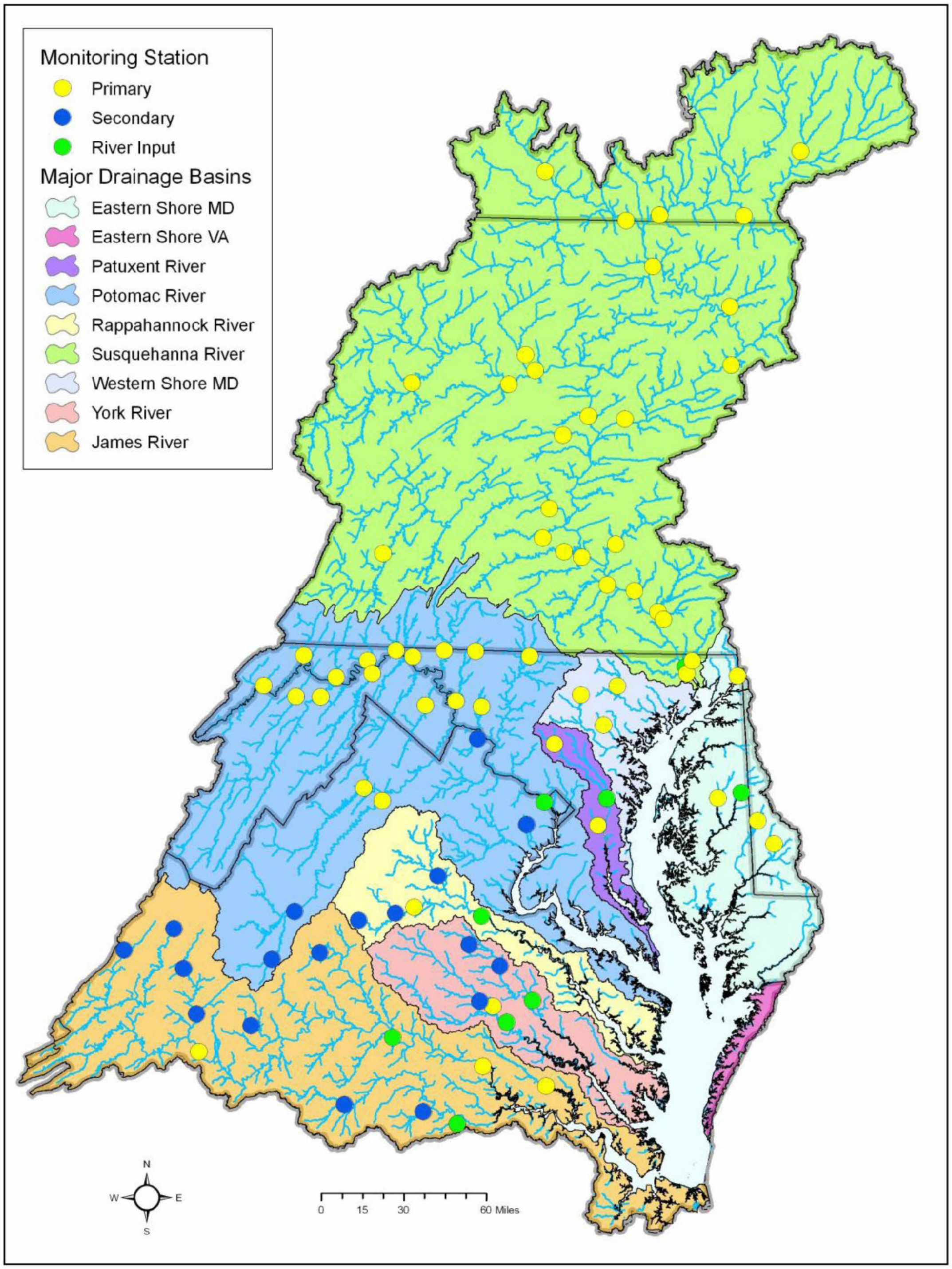
5.2.2 Partnership's Watershed Monitoring Network

The Chesapeake Bay watershed water-quality network is a network of 85 streamflow gauges and water-quality sampling sites operated across the Bay watershed (Figure 5-5). The network is an essential component to reporting, tracking, and modeling nitrogen, phosphorus, and sediment concentration and loads in the Chesapeake Bay watershed as it provides the only consistent, coordinated monitoring effort across all seven Chesapeake Bay watershed jurisdictions. Data from the watershed monitoring network sites have been used to develop, calibrate and verify the Phase 5.3 Chesapeake Bay Watershed Model (Bay Watershed Model).

The CBP partnership designed the watershed water-quality sampling network in 2004 and signed a MOU in September 2004 to implement the network (Chesapeake Bay Watershed Partners 2004). The watershed monitoring network has undergone multiple scientific reviews since its inception (e.g., STAC 2005a, 2005b; MRAT 2009). After a 2009 review of the monitoring network, the original objectives of the network were modified to reflect a balance between the long-term monitoring goals of CBP partners and the increased need for tracking changes that could result from management actions (restoration) and other changes occurring in the watershed. The new objectives, as adopted by the partnership through the CBP's Management Board (MRAT 2009), are as follows:

1. Measure and assess the status and trends of nutrient and sediment concentrations and loads in major tributaries and subwatersheds and selected tributary strategy basins
2. Provide data suitable for the assessment of factors affecting nutrient and sediment status and trends from major pollutant source sectors
3. Measure and assess the effects of targeted management and land-use change
4. Improve calibration and verification of partners' watershed models
5. Support spatial and topical prioritization of pollutant reduction, restoration, and preservation actions

The network has 85 sites consisting of 67 sites fully implemented (primary) and another 18 sites partially implemented (secondary) (Figure 5-5). All primary sites have the following: (1) continuous USGS streamflow gauging; (2) 20 water chemistry samples collected annually over a range of stream flow conditions (12 base flow and 8 storm flow); (3) nitrogen, phosphorus, and sediment analyses; and (4) collection techniques that ensure representative samples. At secondary sites, all the requirements for primary sites are met except storm sampling (Figure 5-5). More than 30 of the primary sites are in locations where monitoring has been coordinated for decades, allowing for trend analysis at the locations. Data analysis is just becoming possible on the remaining sites as they accumulate close to 5 years of data.



Source: Chesapeake Bay Program

Figure 5-5. Watershed monitoring network.

5.2.3 Data Quality and Access

The CBP partnership has a QA program that covers all internal and external activities that involve the collection, evaluation, or use of environmental data. The QA program meets the requirements of EPA Order CIO 2105.0 for EPA programs, i.e., the American National Standard ANSI/ASQC E4-1994. The QA program also satisfies the requirements of the *EPA Information Quality Guidelines*,[1] which describes how EPA organizations meet the Data Quality Act (section 515(a) of the Treasury and General Government Appropriations Act for Fiscal Year 2001 (Public Law 106-554; H.R. 5658). The CBP Office *Quality Assurance Program Management Plan*[2] describes the QA systems and is reviewed regularly and approved by EPA Region 3 (USEPA 2010k).

The CBP partnership has maintained a research-quality monitoring program for Chesapeake Bay tidal waters since the late 1980s when standardized sampling, analytical, and data management procedures were developed and coordinated with the then Maryland Office of Environmental Programs and the Virginia State Water Control Board. River Input monitoring was then initiated at the major fall lines to measure nutrient and sediment loadings from the watershed's nine largest rivers and integrated into the partnership's QA program. The coordinated watershed water quality monitoring was later expanded upstream into rivers and streams across the Bay watershed, with seven watershed jurisdictions using comparable protocols (Chesapeake Watershed Partners 2004).

Each monitoring program produces a continuous record of high-quality data. As each of the monitoring programs is designed to detect trends in water quality constituents, trend analyses require very reproducible data over time collected at the lowest possible limits of detection. Changes in methods, laboratories, instruments, sampling sites, and such, can affect the results, so changes are carefully evaluated and approved to preserve the reproducibility of the data sets over time. Data comparability among watershed jurisdictions is reviewed every 3 months through the Chesapeake Bay Coordinated Split Sample Program (USEPA 1991b). The CBP Office evaluates the accuracy of laboratory data every 3 months by reviewing results of performance evaluation samples, i.e., CBP Blind Audit Samples[3] and UGSS Standard Reference Samples.[4]

The tidal monitoring program is designed to represent the complexities of the estuary. Every 2–4 weeks, a three-dimensional view is obtained by sampling various depths from the surface to the bottom of the water column at approximately 139 stations, with each Bay segment having one or more sampling sites. Sites are sampled at least once each month. Standardized sampling and analytical methods are used to detect low levels of nutrients, chlorophyll and particulates; these methods were approved by EPA in 1986 and are still used today (USEPA 1996).

The Chesapeake Bay watershed monitoring network is designed to measure the discharge of nutrient and sediment loads from 85 sites in watersheds larger than 1,000 square kilometers. Routine samples are collected monthly with additional storm-event samples to obtain a range of discharges and loadings. The six jurisdictions, the Susquehanna River Basin Commission, and

[1] See http://www.epa.gov/quality/informationguidelines/.
[2] See http://archive.chesapeakebay.net/pubs/quality_assurance/cbpoqmp5_01.pdf.
[3] See http://nasl.cbl.umces.edu/.
[4] See http://bqs.usgs.gov/srs/.

Online Chesapeake Bay Monitoring Networks data submission, data access, and quality assurance resources:

Chesapeake Bay Program Data Hub
http://www.chesapeakebay.net/dataandtools.aspx?menuitem=14872

CBP Water Quality Database
http://www.chesapeakebay.net/data_waterquality.aspx

CBP Map of Mainstem and Tributary Stations
http://archive.chesapeakebay.net/pubs/maps/2004-149.pdf

CBP Online Water Quality Data Dictionary
http://archive.chesapeakebay.net/data/data_dict.cfm?DB_CODE=CBP_WQDB

USGS all use the same set of standardized CBP protocols that are based on USGS sampling methods and EPA-approved analytical methods (CBP 2008).

All federally funded organizations performing sampling, analysis and data analysis as part of the tidal and watershed monitoring networks have EPA-approved QA plans and standard operating procedures that conform to the CBP Recommended Guidelines for Sampling and Analysis[5] (USEPA 1996). These guidelines specify sampling and analytical methods, precision and accuracy checks and tolerances, and documentation requirements. The QA documents for individual partner organizations responsible for components of the larger tidal and watershed water quality monitoring networks are on the CBP partnership website at http://www.chesapeakebay.net/qualityassurance_wq.aspx.

The CBP Office conducts routine audits of field and laboratory operations to ensure that the procedures are carried out according to their approved QA plans. Several organizations conduct their own internal field audits or require the use of accredited environmental laboratories.

The Analytical Methods and Quality Assurance Workgroup[6] has been part of the CBP organizational structure since 1988. The workgroup, composed of field sampling team and laboratory managers provides technical peer reviews of data collection and reporting activities to ensure consistency among the sampling and analytical organizations (Figure 5-6). The Workgroup reviews blind audit and coordinated split sample results and identifies potential causes of observed differences. Special studies or corrective actions might be necessary to ensure inter-laboratory agreement. If differences are found to affect subsequent data analyses, the associated bias is quantified and documented in Data and Information Tracking System (DAITS). DAITS is a registry of technical investigations regarding the quality and use of water quality data sets.

5.2.4 Data Submission and Quality Assurance

Water quality data are submitted electronically to the CBP Office by the participating data providers (Figure 5-6) according to data submission requirements specified in the federal grant/cooperative agreement assistance award provisions (USEPA 2010b). Agencies collecting data as part of the Chesapeake Bay tidal water quality monitoring program submit data to the Chesapeake Information Management System (CIMS) within 60 days of the end of the month in which the sample was collected. Watershed water quality monitoring data are submitted once per year. The Data Upload and Quality Assurance Tool (DUQAT) is an automated online tool available to data submitters who manage the processing of their data before it is included in the

[5] See http://www.chesapeakebay.net/committee_analyticalmethodsworkgroup_projects.aspx?menuitem=16701.
[6] See http://www.chesapeakebay.net/committee_analyticalmethodsworkgroup_info.aspx.

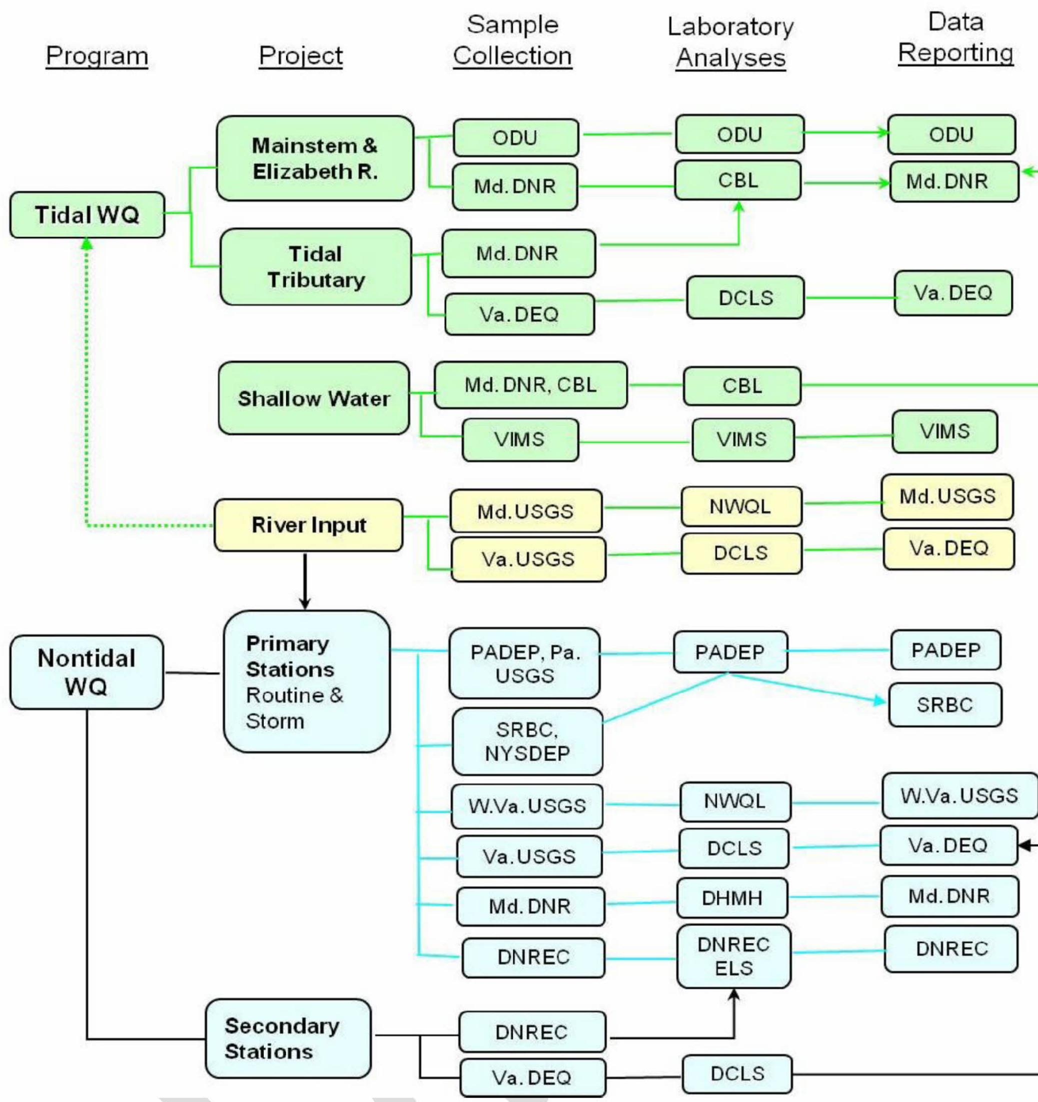
database. DUQUAT proceeds through more than 150 format and QA checks, provides a report on errors and outliers and, after formal acceptance by the submitter and CBP data manager, loads the data into the CIMS Water Quality Database. The final report from the QA-checks is archived and available for future reference. The *CIMS Data Upload & Quality Assurance Tool User's Guide*[7] gives directions on how to use the tool and shows the correct table formats (Lane 2004). The database for the Chesapeake Bay watershed monitoring network is being developed; however, data submittals from the participating partners will be required to pass through a modified version of DUQAT before acceptance into the database.

After a water quality data submission has passed through DUQAT, and within 24 hours after acceptance, the data are added to the Water Quality Database and made available to the public on the CBP Data Hub.[8] The Data Hub interface provides access to several types of data related to the Chesapeake Bay. It provides links to CBP water quality, living resources (benthic and plankton), and nutrient point source databases, and external links to partner data sets and databases available on the Data Hub. A data download tool is available for each CBP database that allows for queries based upon user-defined inputs such as geographic region and date range. Each query results in a downloadable, tab- or comma-delimited text file that can be imported to any program (e.g., SAS, Excel, and Access) for further analysis. About 12,000 sampling events comprising 8,000,000 data records are housed in the Water Quality Database from 1984 to present that are available to the public (scientists, data analysts, and private citizens).

All required data submissions from the monitoring programs described must meet the data requirements set forth in the *Chesapeake Bay Program Guidance for Data Management*, October 1997, Metadata Guidelines, and CBP Program Data Dictionaries developed by the Information Management Subcommittee of the CBP. All living resources data deliverables are sent in a format compliant with Appendix E of the *2000 Users Guide to Living Resources Data* when submitted to the CBP (USEPA 2000).

Database documentation and metadata links for the various sampling programs are available for viewing and download. A map of mainstem and tributary monitoring stations[9] is available and helps users query for data in a specific geographic region of the watershed. The *1993 Guide to Using CBP Water Quality Monitoring Data*[10] describes the Chesapeake Bay tidal water quality monitoring program in general and provides detailed information about the existing database. A 2009 draft update to that document is being reviewed. The *Water Quality Database Design and Data Dictionary*[11] is a resource that defines the development of the database and provides a detailed description of the tables and data in the database. The online version of the Water Quality Data Dictionary provides the up-to-date CIMS and CBP codes used in the Water Quality Database.

[7] See http://archive.chesapeakebay.net/pubs/DUQATUsersGuide.pdf.
[8] See http://www.chesapeakebay.net/dataandtools.aspx?menuitem=14872.
[9] See http://archive.chesapeakebay.net/pubs/maps/2004-149.pdf.
[10] See http://archive.chesapeakebay.net/pubs/wquser.pdf.
[11] See http://archive.chesapeakebay.net/pubs/cbwqdb2004_RB.PDF.



Source: Chesapeake Bay Program
Laboratory Abbreviations:
CBL – University of Maryland Chesapeake Biological Laboratory
DCLS – Virginia Department of Consolidated Laboratory Services
DHMH – Maryland Department of Health and Mental Hygiene
DNREC – Delaware Department of Natural Resources and Environmental Quality
DNREC ESL – Delaware Natural Resources Environmental Laboratory Services
Md. DNR – Maryland Department of Natural Resources
NWQL – National Water Quality Laboratory
NYSDEP – New York State Department of Environmental Conservation
ODU – Old Dominion University Water Quality Laboratory
PADEP – Pennsylvania Department of Environmental Protection
SRBC – Susquehanna River Basin Commission
USGS – United States Geological Survey (Md., Pa., Va. & W.Va. Water Science Centers)
Va. DEQ – Virginia Department of Environmental Quality
VIMS – Virginia Institute of Marine Science

Figure 5-6. Chesapeake Bay tidal and watershed water quality monitoring networks' participants arrayed by their role in sample collection, laboratory analysis, or data reporting.

5.2.5 Monitoring Applications in Chesapeake Bay TMDL Development

Data collected through the Chesapeake Bay tidal and watershed monitoring networks, described above, have been applied in numerous ways, supporting the development of the Bay TMDL:

- Used to develop the original Chesapeake Bay segmentation scheme and its subsequent refinements (USEPA 2004b, 2005)
- Used in derivation of the DO, water clarity, SAV restoration acreage and chlorophyll *a* criteria published by EPA on behalf of the partnership (USEPA 2003a)
- Used in the delineation of the spatial boundaries of the five Chesapeake Bay tidal water designated uses (USEPA 2003c, 2004e, 2010a)
- Used in the original development and ongoing refinement of the Chesapeake Bay water quality criteria assessment procedures (USEPA 2003a, 2004a, 2007a, 2007b, 2008a, 2010a)
- Used by four Bay jurisdictions to assess achievement of their respective Chesapeake Bay WQS and development of their section 303(d) lists (USEPA 2007a)
- Used in the development, calibration, and verification of the Phase 5.3 Chesapeake Bay Watershed Model and Chesapeake Bay Water Quality Model (USEPA 2010j)

5.3 Modeling Framework Overview

Since the early 1980s, the CBP has developed and applied multiple generations of linked environmental models to help evaluate the response of Chesapeake Bay water quality to various management scenarios and programmatic approaches (Figure 5-7). The fourth and fifth generations of some of these environmental models have been applied to support the Chesapeake Bay TMDL development.

The Chesapeake Bay models are state-of-the-science, but they are just one of the tools in the TMDL analysis that also includes monitoring and environmental research. The models produce estimates, not perfect forecasts. Hence, they reduce, but do not eliminate, uncertainty in environmental decision making. Used properly, the models provide best estimates for developing nutrient and sediment reductions that are most protective of the environment. Ultimately, the Chesapeake Bay TMDL was based on the overall corroboration of the Chesapeake Bay models, monitoring, and environmental research.

The two major components of the Chesapeake Bay TMDL modeling framework are the Phase 5.3 Chesapeake Bay Watershed Model and the Chesapeake Bay Water Quality and Sediment Transport Model (Bay Water Quality Model). Several other models and tools were used to provide critical inputs or to facilitate parameterizing the Bay Watershed Model to run various management scenarios (Table 5-1).

Table 5-1. Modeling tools supporting development of the Chesapeake Bay TMDL.

Model	Function
Chesapeake Bay Airshed Model	Provides estimates of wet and dry atmospheric deposition to the Bay watershed and water quality models
Chesapeake Bay Land Change Model, Version 4	Provides annual time series of land uses to the Bay Watershed Model including projected land uses out to 2030
Chesapeake Bay Spatially Referenced Regressions on Watershed Attributes (SPARROW) Model	Provides a general calibration check on Bay Watershed Model land use and riverine loads
Chesapeake Bay Scenario Builder	Facilitates the creation of input decks for Bay Watershed Model management scenarios
Phase 5.3 Chesapeake Bay Community Watershed Model	• Simulates loading and transport of nutrients and sediment from various sources in the Bay watershed • Provides estimates of watershed loads resulting from various management scenarios
Chesapeake Bay Water Quality/Sediment Transport Model	• Simulates estuarine hydrodynamics, water quality, sediment transport, and key living resources such as underwater grasses, oysters and menhaden • Predicts Bay water quality resulting from various management scenarios • Ensures allocated loads under the Bay TMDL will meet jurisdictions' WQS Bay criteria
Chesapeake Bay Criteria Assessment Program	Assesses attainment of the jurisdictions' WQS Bay criteria using a unique combination of Bay Water Quality Model management scenario outputs and Bay water quality monitoring data
Chesapeake Bay Climate Change Simulation	Uses aspects of downscaled data from Global Climate Models, the Bay Watershed Model, and the Bay Water Quality Model to simulate climate change effects in the Chesapeake Bay and its watershed

The models used to develop the Chesapeake Bay TMDL simulate the same 10-year hydrologic period from 1991 to 2000. The models are linked together so that the output of one simulation provides input data for another model (Figure 5-7). For example, the nitrogen outputs from the Chesapeake Bay Airshed Model (CBAM) affect the nitrogen input from atmospheric deposition to the Bay Watershed Model. The Bay Watershed Model, in turn, transports the total nutrient and sediment loads, including the contributions from atmospheric deposition, to the Bay Water Quality Model. The Bay Water Quality Model, in turn, simulates the effects of the nutrient and sediment loads generated by the Bay Watershed Model, and the effects of direct atmospheric deposition to tidal surface waters on Bay water quality (e.g., DO, water clarity, chlorophyll *a*), exchange of nutrients and oxygen with bottom sediments, and living resources (e.g., underwater Bay grasses, algae, zooplankton, bottom-dwelling worms and clams, oysters, and menhaden).

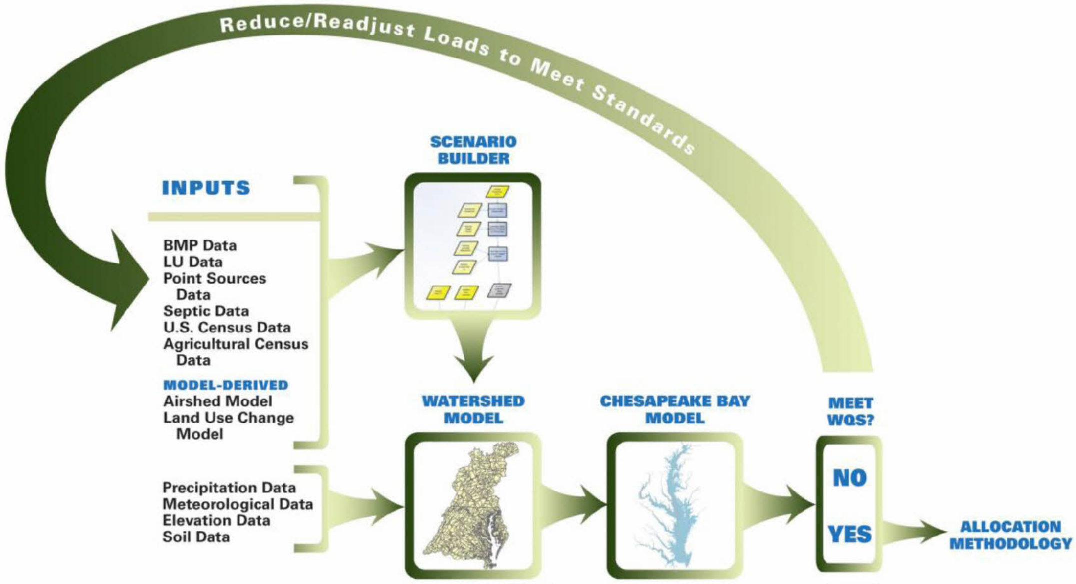


Figure 5-7. Chesapeake Bay TMDL modeling framework.

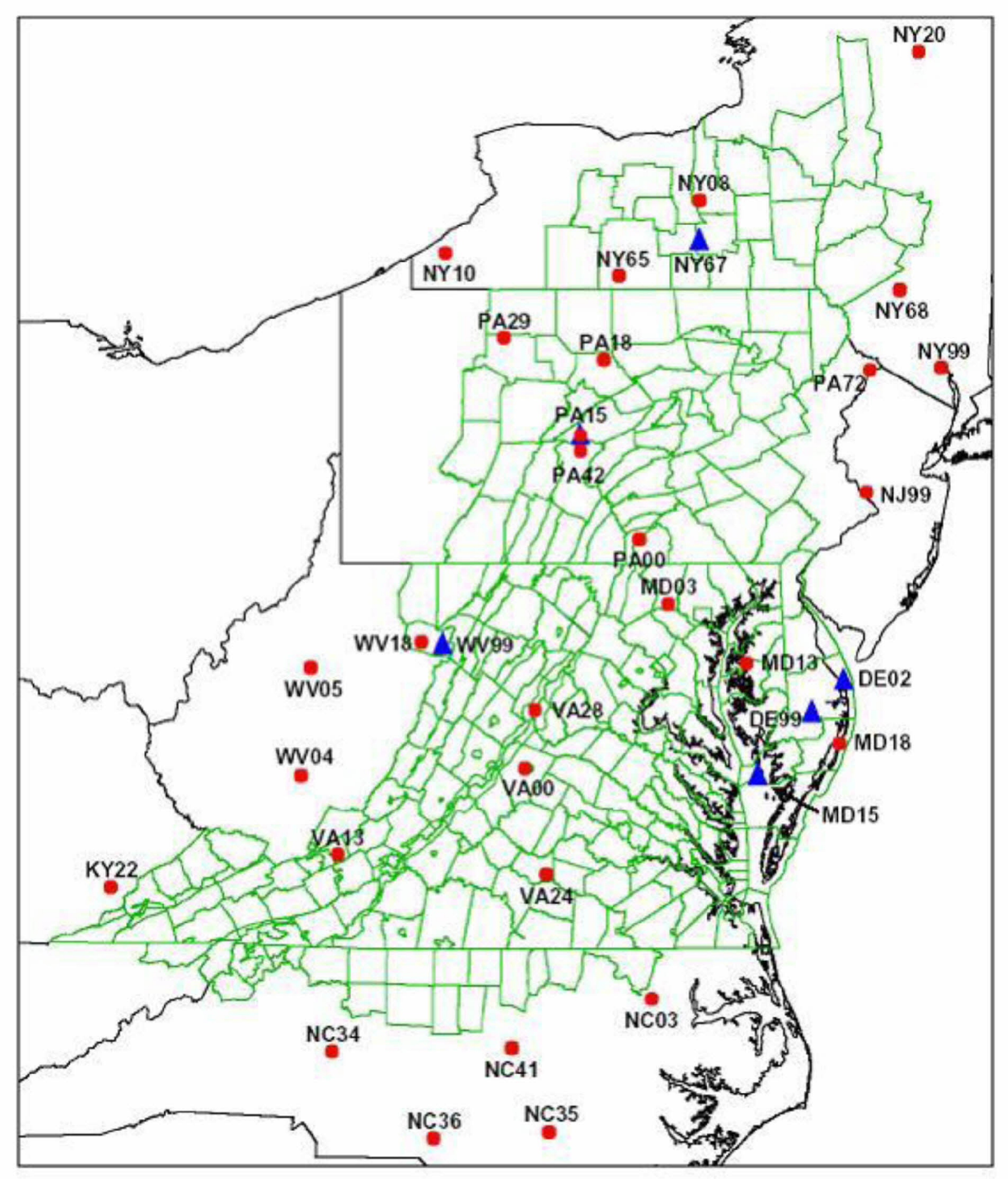
The following sections provide additional details about each of the Bay models and other decision support tools used to support development of the Chesapeake Bay TMDL and the linkages between the various models and tools. For each model/tool, the sections provide a general description of it and how the model was used in developing the Chesapeake Bay TMDL. Links to more detailed, online documentation are provided.

5.4 Chesapeake Bay Airshed Model

The Chesapeake Bay Airshed Model (CBAM) provides estimates of nitrogen deposition resulting from changes in emissions from utility, mobile, and industrial sources because of management actions or growth.

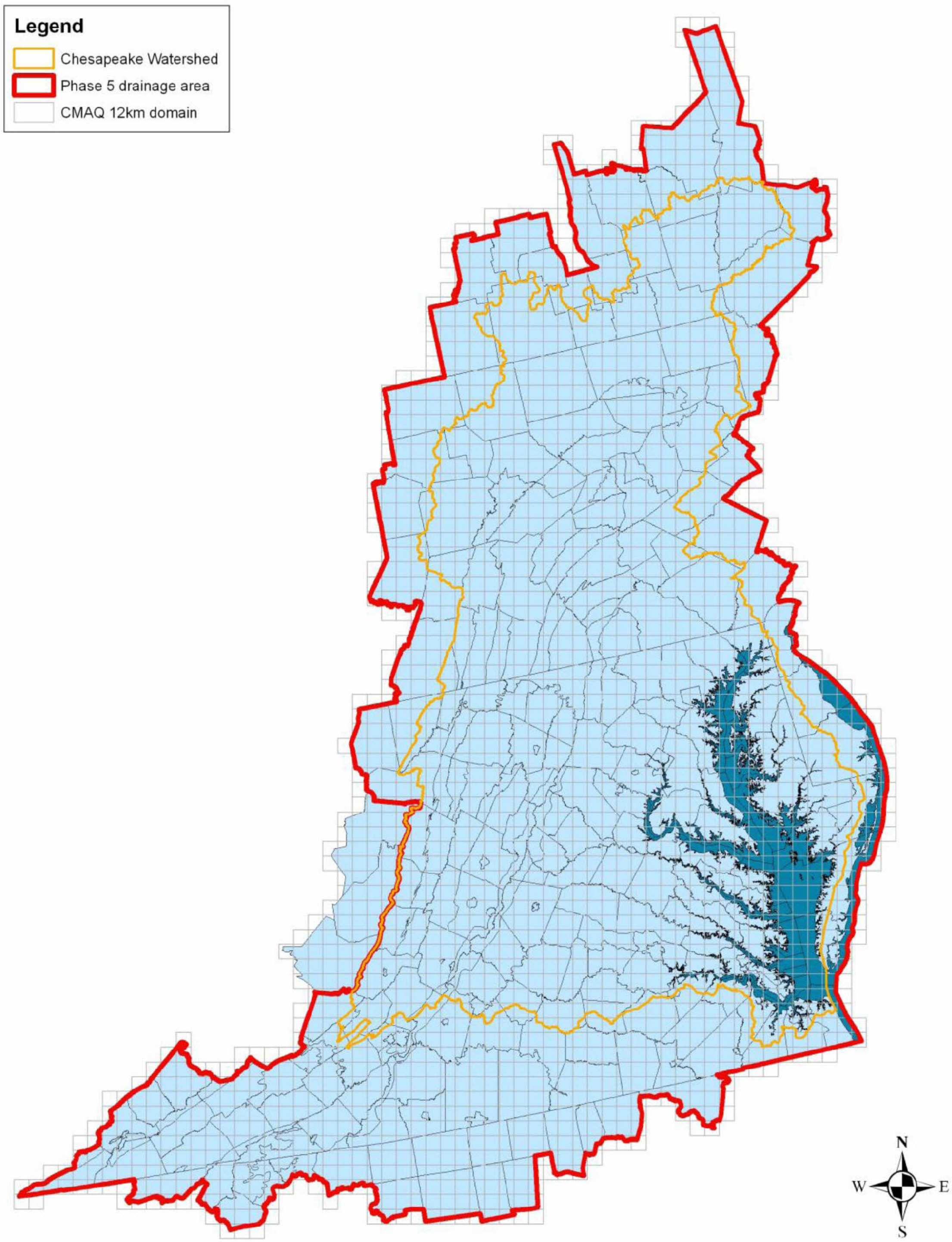
The CBAM was used to provide inputs of nitrogen from wet and dry deposition to the Bay Watershed Model and to the Bay Water Quality Model. The CBAM is linked to the Bay Watershed Model through atmospheric deposition to land surfaces and to the Bay Water Quality Model through atmospheric deposition to water surfaces of the tidal Chesapeake Bay (USEPA 2010j).

The CBAM combines a regression model of wet deposition (Figure 5-8) (Grimm and Lynch 2000; 2005), and a continental-scale air quality model of North America called the Community Multiscale Air Quality Model (CMAQ) for estimates of dry deposition (Figure 5-9) (Dennis et al. 2007; Hameedi et al. 2007). Wet deposition occurs during precipitation events and contributes to the loads only during days of rain or snow. Dry deposition occurs continuously and is input at a constant rate every day.



Source: Grimm and Lynch, 2005.

Figure 5-8. Atmospheric deposition monitoring stations used in the airshed regression model.



Source: Dr. Robin Dennis, USEPA/ORD/NERL/AMAD/AEIB.

Figure 5-9. The CMAQ 12 km grid over the Phase 5 domain.

The CMAQ scenarios include the management actions required by the Clean Air Act (CAA) in 2010, 2020, and 2030. The future year scenarios reflect emissions reductions from national control programs for both stationary and mobile sources, including the Clean Air Transport Rule (Replacement for the Clean Air Interstate Rule), the Tier-2 Vehicle Rule, the Nonroad Engine Rule, the Heavy-Duty Diesel Engine Rule, and the Locomotive/Marine Engine Rule.

The CMAQ provides monthly constants for dry deposition. It requires a variety of input files that contain information pertaining to the entire North American continent. Those include hourly emissions estimates and meteorological data in every grid cell and a set of pollutant concentrations to initialize the model and to specify concentrations along the modeling domain boundaries. The initial and boundary concentrations were obtained from output of a global chemistry model.

The CMAQ simulation period is for one year, 2002, characterized as an average deposition year. The 2002 CMAQ simulation year was used to provide the monthly dry deposition estimate for each year of the 1985 to 2010 Bay simulation.

The wet deposition regression model provides hourly wet deposition loads to each land-segment on the basis of each land-segment's rainfall. The regression model uses 29 National Atmospheric Deposition Program monitoring stations and 6 AirMoN stations to form a regression of wetfall deposition in the entire Phase 5 Model Domain over the entire simulation period (see Appendix M).

To account for wet deposition of nitrogen, EPA both developed a specific TMDL LA for the direct nitrogen atmospheric deposition onto tidal surface waters of the Chesapeake Bay and accounted for air deposition of nitrogen in the LAs to the watershed. The Bay TMDL air allocation reflects the modeled nitrogen deposition to the Bay, taking into account the reduction in air emissions expected from sources regulated under existing or planned federal CAA authorized programs (see Section 6.10 and Appendix M).

Detailed information related to the CBAM and its application in the Chesapeake Bay TMDL is available in Section 5 of the Phase 5.3 Chesapeake Bay Watershed Model Report (USEPA 2010i) at http://www.chesapeakebay.net/model_phase5.aspx?menuitem=26169.

5.5 Chesapeake Bay Land Change Model

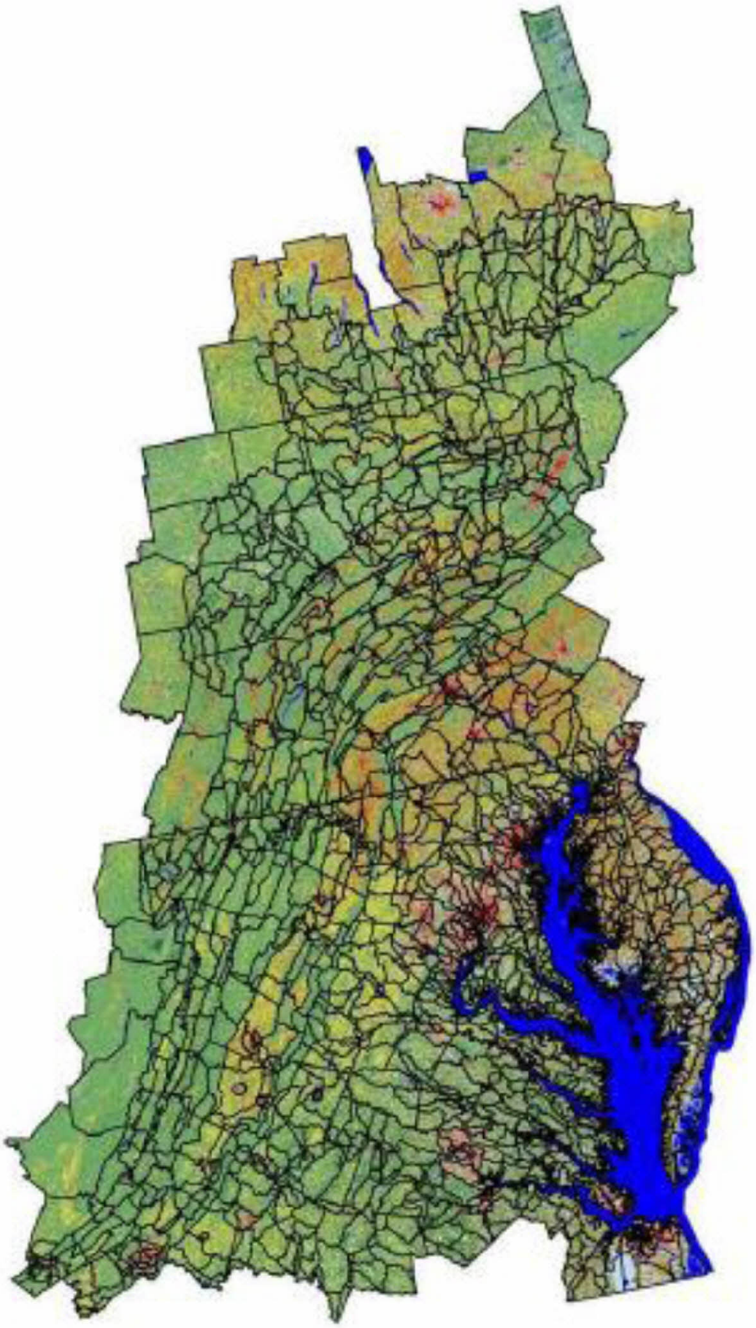
The Chesapeake Bay Phase 5.3 model makes use of annually changing land use profiles derived from the Chesapeake Bay Land Change Model.

5.5.1 Motivations for Developing Future Land Use Estimates

A major challenge facing water resource managers today is how to maintain progress restoring the Chesapeake Bay in the face of continued population and urban development. The Chesapeake Bay Land Change Model (Land Change Model) was developed to help address this management challenge. In conjunction with the Bay Watershed Model, the Bay Land Change Model can be used to assess potential future changes in nutrient and sediment loads to the Bay.

5.5.2 Scale of Chesapeake Bay Land Change Model Future Land Use Estimates

To meet the data requirements of Phase 5.3 Chesapeake Bay Watershed Model, the Bay Land Change Model forecasts change at the Bay Watershed Model segment scale. The latest version of the Bay Land Change Model includes more than 2,000 modeling segments (e.g., polygons) in the Bay watershed and intersecting counties (Figure 5-10). The segments were created on the basis of an intersection of county boundaries, major topographic divides, and a 1:250,000 scale river reach drainage area network. Because the modeling segments are within counties, all data generated at the modeling segment scale can also be provided at the county scale for local review and comment.



Source: Chesapeake Bay Program Office.

Figure 5-10. The Land Change Model.

5.5.3 Components of Chesapeake Bay Land Change Model Future Land Use Estimates

In support of the CBP management concerns, researchers from USGS, EPA, Shippensburg University, and a private consultant developed the Chesapeake Bay Land Change Model, which combines the strengths of a growth allocation model or *GAMe* (Reilly 2003), with those of a cellular automata model, *SLEUTH* (slope, land use, excluded land, urban extent, transportation, and hillshade) (Clarke et al. 1997; Jantz et al. 2003). GAMe projects future urban developed area at the watershed modeling segment scale by fitting total housing unit trends over the 1990s to a Gompertz (exponential *S*-shaped) curve that is then used to extrapolate housing trends to the year 2030. County population projections converted to county scale estimates of total housing demand are used to constrain the modeling segment scale forecasts generated using the Gompertz Curve. After the model segment scale forecasts of housing demand are adjusted to match the county scale housing demand totals, they are converted to an estimate of future urban developed area using segment-specific ratios of urban developed land cover area to total housing units.

The proportions of structural development growth occurring on farmland, forest land, sewer, septic, and within existing developed boundaries are determined uniquely for each watershed modeling segment using the SLEUTH growth model, a stochastic cellular automata model customized for application in the Chesapeake Bay watershed by Goetz and Jantz (2006). SLEUTH extrapolates historic rates and patterns of urban developed growth into the future using satellite derived imagery of 1990 and 2000 impervious cover. SLEUTH was calibrated separately in 15 different county clusters in the Bay watershed. Counties were clustered according to shared characteristics of urban developed growth, commuting patterns, and state and ecoregion boundaries. SLEUTH uses a Monte Carlo method to generate multiple simulations of future growth, which are combined to create a probability map of future urban development. The output from SLEUTH is a 30-m resolution probability raster data set that indicates the probability of urban developed growth in the year 2030 with values ranging from 0 to 100 percent.

The patterns of probable growth can vary for each cluster of counties by the coefficients used to calibrate SLEUTH in each cluster. The patterns and levels of probable urban developed can also vary within a county by local factors of attraction and repulsion. The factors are represented in a 30-m resolution raster data set referred to as an *exclusion layer*. Local areas *off limits* to development can include public lands, conservation easements, rurally zoned lands, steep slopes (greater than 21 percent grade), emergent wetlands, and open water. For the Bay watershed, an exclusion layer was created in a GIS using information on public and protected lands, generalized zoning, and land cover. Values greater than 50 are relatively repulsive to growth with 100 being completely excluded. Values less than 50 are relatively attractive to growth (e.g., areas zoned for moderate or high density growth). The midpoint, 50, is neutral.

The probability output from SLEUTH is overlaid onto a raster land cover data set to determine the relative proportions of land cover classes and sewer areas affected by future growth. For example, if a cell with a 50 percent probability of becoming developed by 2030 overlays a forest cell in the land cover map, 50 percent of that cell is considered forest loss. For each modeling segment, the total acreage of all land cover classes converted to urban developed are summed and divided by the total of urban developed acreage forecasted in the modeling segment. That process generates relative proportions of future growth by land cover class for each modeling segment. Multiplying those proportions by the acreage of forecasted growth (generated by GAMe) determines how much acreage to subtract or add in future years to the Phase 5 Watershed Model 2002 baseline land use classes.

The Bay Land Change Model also includes a Sewer Model to estimate the population on sewer and septic in the years 2000 and 2030. Where local data were not available, a population density raster data set derived from year 2000 Census Block Group data and detailed road vector files were used to represent probable sewered areas in the year 2000. The approach captures 81 percent of Maryland's mapped residential sewered areas on the basis of a one-to-one cell comparison. That approach also compares favorably with survey data in Virginia representing households with sewer service in the 2001 to 2005 period.

Modeled sewered areas in the year 2000 were expanded along existing roads by 300 m to 2,000 m to represent possible expansion of the sewer network through the year 2030. Forecasted population values for each watershed modeling segment were derived by converting the housing demand forecasts into estimates of future population. Future populations on sewer and septic were estimated by overlaying the SLEUTH probability map onto the modeled sewer service areas for 2030 to derive proportions of growth on sewer and septic, which were then multiplied by the forecasted population in each modeling segment. The proportions of growth on sewer and septic were kept constant for all interim year forecasts between 2000 and 2030. The percent change in population within each sewer service area was used to estimate the percent change in flow for all wastewater treatment plants in or close to each service area.

More detailed information on the Chesapeake Bay Land Change Model and its application in the Chesapeake Bay TMDL is available in Section 4 of the Phase 5.3 Chesapeake Bay Watershed Model Report (USEPA 2010i) at http://www.chesapeakebay.net/model_phase5.aspx?menuitem=26169.

5.6 Chesapeake Bay SPARROW Model

The USGS developed a set of spatially referenced regression models to provide additional spatial detail on nutrient sources and transport processes in the Bay watershed. The SPARROW (SPAtially Referenced Regression On Watershed attributes) model integrates monitoring data with landscape information and uses statistical methods to relate water-quality monitoring data to upstream sources and watershed characteristics that affect the fate and transport of constituents to streams, estuaries, and other receiving waterbodies (Preston et al. 2009). SPARROW is watershed based and designed for use in predicting long-term average values such as concentrations and delivered loads to downstream receiving waters.

For additional information on Chesapeake Bay SPARROW modeling, see the following resources:

SPARROW fact sheet

http://pubs.usgs.gov/fs/2009/3019/

National SPARROW home page

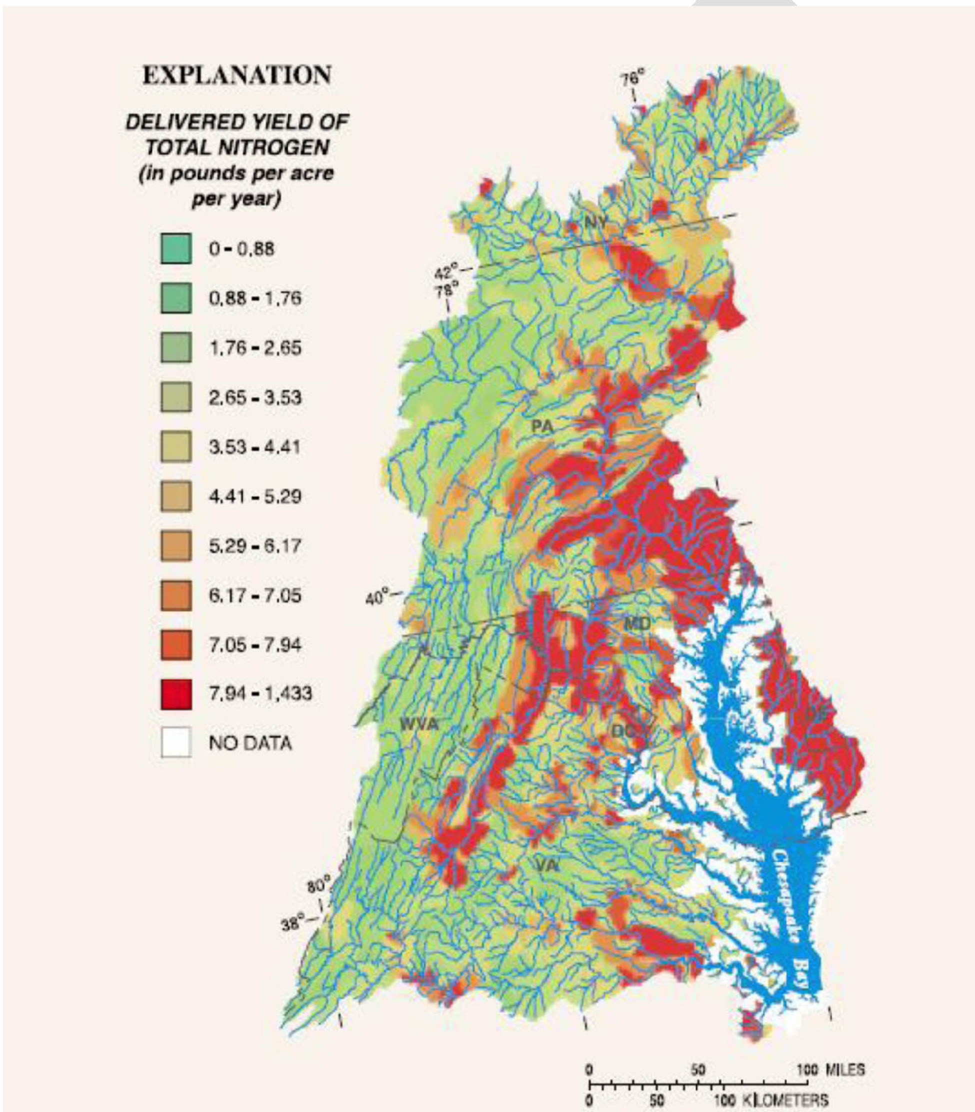
http://water.usgs.gov/nawqa/sparrow/

Chesapeake Bay Specific

http://md.water.usgs.gov/publications/wrir-99-4054/html/index.htm
http://md.water.usgs.gov/publications/ofr-2004-1433/
http://chesapeake.usgs.gov/coast/restorationmapper.html

Statistical methods are used to explain in-stream measurements of water quality in relation to upstream sources and watershed properties (e.g., soil characteristics, precipitation, and land cover).

Among its outputs, the SPARROW model can be used to quantify *incremental* yield or edge-of-field loading, which is the amount (load per area) of total nutrients or sediment generated in each reach basin independent of upstream load (Figure 5-11). The Chesapeake Bay SPARROW models provide loading information for three separate periods, the late 1980s, the early 1990s, and the late 1990s (Brakebill and Preston 2004). For the Chesapeake Bay watershed modeling and TMDL development effort, EPA used the results of the SPARROW model as a data source for estimating average edge-of-field targets when developing and calibrating the Phase 5.3 Chesapeake Bay Watershed Model (USEPA 2010j).

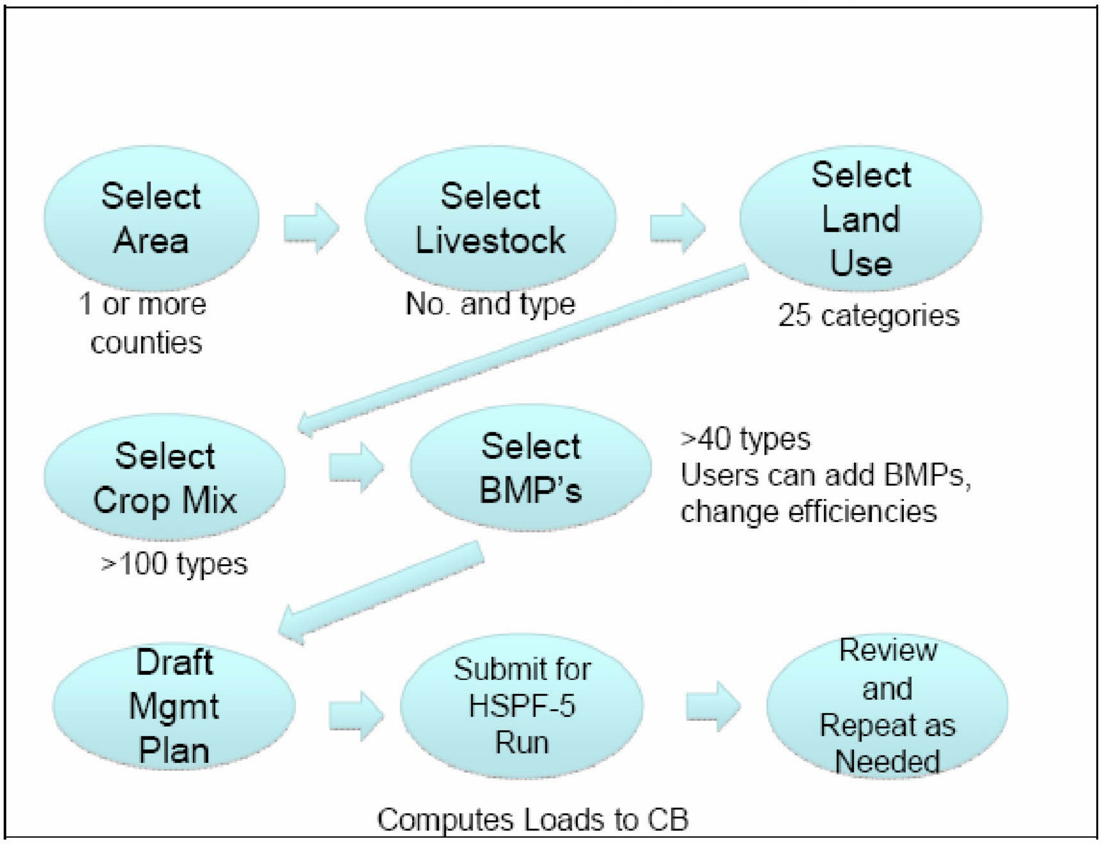


Source: Preston and Brakebill, 1999.

Figure 5-11. An example of SPARROW Model output showing delivered yield of total nitrogen in the Chesapeake Bay watershed during 1987.

5.7 Scenario Builder

Scenario Builder is a standalone data pre-processor for the Phase 5.3 Chesapeake Bay Watershed Model. It is designed to track the land use-related nutrient processes for the multiple land use-related sources in the watershed and to facilitate parameterization of those sources for watershed model scenarios to be run through the Bay Watershed Model (Figure 5-12). Scenario Builder generates information that is used to simulate loads related to animal production areas, manure storage, application of manure and fertilizers, septic inputs, plant growth/uptake and BMP implementation. Scenario Builder can handle data at a variety of levels, including land-river segment, river segment, land segment, county, state and basin, tributary strategy basin, or state and can vary by the BMP in question. Scenario Builder is designed so that users may select an area of one or more counties, the livestock types and the number of animals, along with a land use using the 25 Watershed Model-HSPF categories and then be able to alter the crop mix that is nested in each of the agricultural land uses along with Best management practices (BMPs).



Source: Scenario Builder Documentation, http://archive.chesapeakebay.net/pubs/SB_Documentation_Final_V22_9_16_2010.pdf

Figure 5-12. Scenario Builder conceptual process.

Scenario Builder provides nutrient loads to the land and the area of soil available to be eroded. Loads are input to the Bay Watershed Model to generate modeled estimates of loads delivered to the Bay. Additional information related to Scenario Builder and its application in Bay TMDL development (USEPA 2010d) is at http://www.chesapeakebay.net/modeling.aspx?menuitem=19303.

For the Bay TMDL, Scenario Builder was used to provide the land use-based scenario inputs to the Phase 5.3 Chesapeake Bay Watershed Model. The seven watershed jurisdictions will continue using it when implementing the Bay TMDL to build model scenarios of their actual and future implementation practices that will, in turn, be run through the Bay Watershed Model to track implementation status and project future implementation rates.

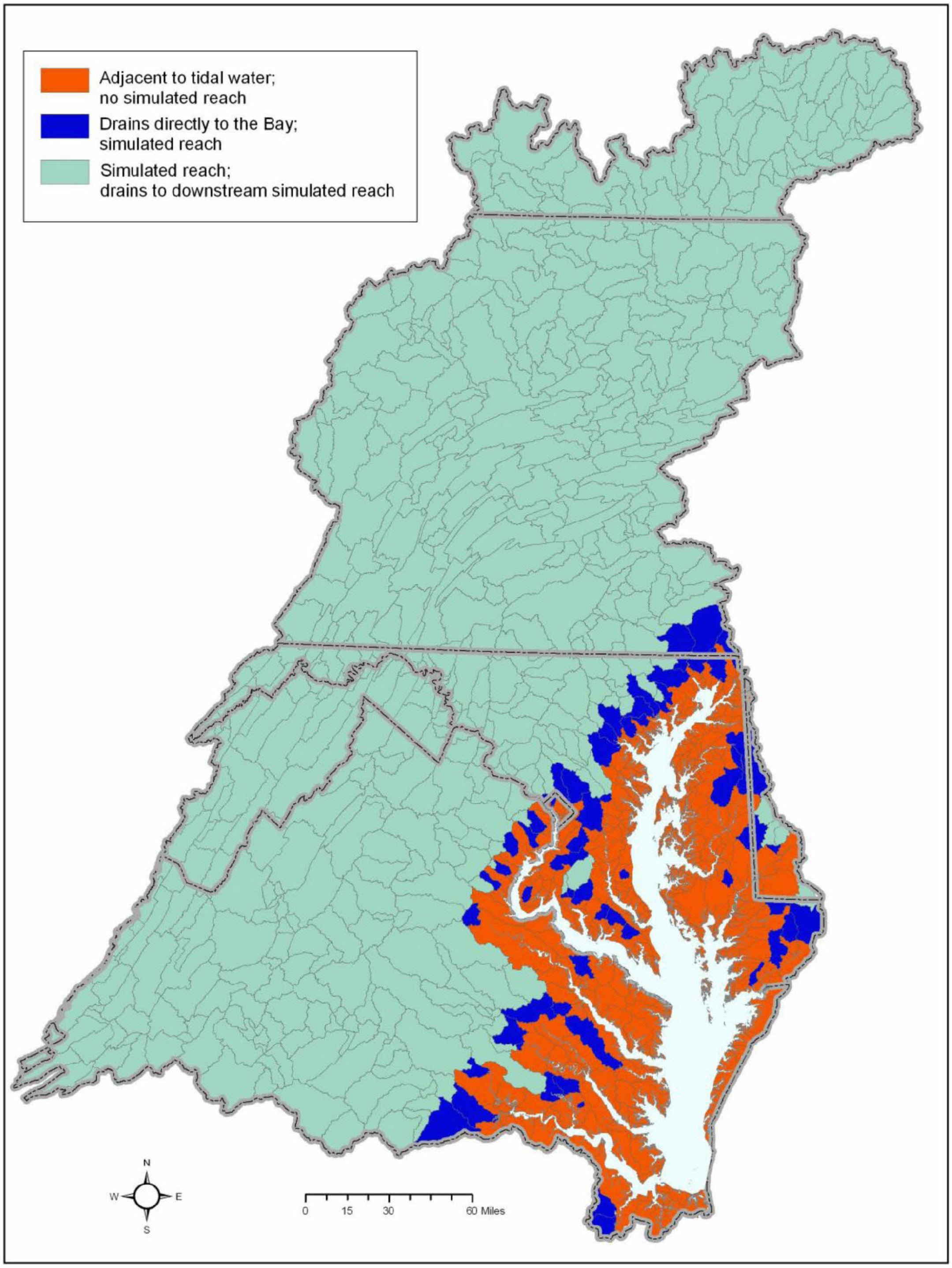
5.8 Phase 5 Chesapeake Bay Watershed Model

The Phase 5.3 Chesapeake Bay Watershed Model is an application of the Hydrologic Simulation Program-Fortran (HSPF) (Bicknell et al. 2005). The segmentation scheme divides the Chesapeake Bay watershed into approximately 1,000 segments/subbasins, the average size is about 64 square miles. About 280 monitoring stations throughout the Chesapeake Bay watershed were used for calibration of hydrology, while approximately 200 monitoring stations were used to calibrate water quality, depending on the constituent being calibrated. There are 530 river-segments with simulated reaches that drain to a simulated downstream reach. There are 62 river-segments with simulated reaches that drain directly to the Chesapeake Bay and 379 river-segments adjacent to tidal waters that are without a simulated reach (Figure 5-13).

The Bay Watershed Model simulation period covers 21 years from 1984 to 2005 to take advantage of more recent and expanded monitoring. The expansion of the model period to a 21-year period required a change in the treatment of land use in model calibration. While the Phase 4.3 Bay Watershed Model and all previous watershed model versions had a constant land use, the Phase 5.3 Bay Watershed Model allows a time series of land use input data to change annually over the 1984 to 2005 simulation period (USEPA 2010i).

As a community model, the Phase 5.3 Bay Watershed Model has open source model code, pre-processors, post-processors, and input data that are freely available to the public (USEPA 2010i). Input data include precipitation information, point sources discharges, atmospheric deposition, and land use (USEPA 2010i). By offering the Bay Watershed Model as a community model, end users—typically TMDL model developers and watershed researchers and implementation plan developers—can use the model independently *as-is* or as a starting point for more detailed, small-scale models (USEPA 2010i). The Phase 5.3 Bay Watershed Model can be downloaded from this ftp site: ftp://ftp.chesapeakebay.net/Modeling/phase5/community/ or the Chesapeake Community Modeling Program's website at http://ches.communitymodeling.org/models/CBPhase5/datalibrary.php.

The Bay Watershed Model simulates the 21-year period (1984–2005) on a one-hour time step (USEPA 2010j). Nutrient inputs from manure, fertilizers, and atmospheric deposition are based on an annual time series using a mass balance of U.S. Census of Agriculture animal populations and crops, records of fertilizer sales, and other data sources. BMPs are incorporated on an annual time step and nutrient and sediment reduction efficiencies are varied by the size of storms. Point source and onsite wastewater management nutrient and sediment contributions are also included in the model. The following sections provide additional details regarding the underlying data used to develop and calibrate the Phase 5.3 Bay Watershed Model.



Source: Phase 5.3 Chesapeake Bay Watershed Model.

Figure 5-13. Segmentation and reach simulation of the Phase 5.3 Chesapeake Bay Watershed Model.

5.8.1 Segmentation

In many HSPF applications, the river segmentation and the land segmentation is the same. Each river segment will have a set of land uses that drain to it and it only. In the Phase 5.3 Bay Watershed Model, the segmentation schemes are separate. Land segments are generally county based because a simulation of a representative acre of each land use type exists in each county. Some counties in mountainous regions where the rainfall patterns varied significantly have been broken out in to several land segments. The segments that result from the intersection of the two segmentation schemes are known as land-river segments (Martucci et al., 2006).

5.8.2 Model Setup

Detailed information related to how the Bay Watershed Model was set up to support development of the Bay TMDL is available in the Phase 5.3 Chesapeake Bay Watershed Model Report. In addition, information related to model representation of land use-related nutrient generating sources is available in the working documentation for the Scenario Builder application (USEPA 2010j). The following paragraphs provide a general description of critical data components underlying the Bay Watershed Model.

Meteorological Data

Meteorological data are critical inputs to the model because precipitation is a primary driver of loading in the Bay. Approximately 500 daily data and 200 hourly data precipitation monitoring stations were used in the Bay Watershed Model. Precipitation is derived from an hourly output regression model of these stations developed by USGS. Meteorological parameters included in the simulation are hourly temperature, solar radiation, wind speed, daily dew point, cloud cover, and potential evapotranspiration. Those parameters were collected from the seven primary meteorological stations in the Chesapeake Bay watershed (USEPA 2010j).

Withdrawals

Water withdrawals are represented in the model as daily amounts from jurisdictions' reported data of monthly or annual withdrawals. Water withdrawals include irrigation use and thermoelectric use, among others. The model takes into account the seasonal cycle of irrigation use. Consumptive uses are modeled as 100 percent removal of the water from the appropriate stream segment, and any resulting wastewater is treated as a separately modeled point source discharge (USEPA 2010j).

Sediment

Soil characteristics were obtained from the Natural Resources Conservation Service Interpretation Records and the National Resources Institute. Sediment delivery from each land use is based on National Resources Institute estimates of annual edge-of-field sediment loads, as determined by the Revised Universal Soil Loss Equation (USEPA 2010j).

Land uses

The watershed model simulates 24 land uses, including 11 types of cropland, 2 types of woodland, 3 types of pasture, 5 types of developed land, and provisions for other special land uses such as surface mines and AFOs (Table 5-2) (USEPA 2010j). Nutrients in the major pervious land uses of woodland, cropland, hay, pasture, and developed pervious are simulated using the AGCHEM modules in HSPF that fully simulate forest or crop nutrient cycling, including uptake by plants. The minor pervious land uses, which are harvested forest, land under construction, nurseries, surface mines, and degraded riparian pasture, are simulated through PQUAL, which represents nutrient export through concentration coefficients. Impervious land uses are simulated through the IQUAL modules, which use accumulation and washoff coefficients to simulate nutrient and sediment export. The final Phase 5.3 land use is available as a sub-county tabular database for the years 1985, 1987, 1992, 1997, 2002, and 2005 at ftp://ftp.chesapeakebay.net/Modeling/phase5/Phase%205.3%20Calibration/Model%20Input/land_use.zip

The Phase 5.3 model input decks including the land use files above are also linked with a brief explanation from the Phase 5 Model page on: chesapeakebay.net.http://www.chesapeakebay.net/model_phase5.aspx.

The Bay Watershed Model uses a continuous time series of land use interpolated from those years.

The principal databases used to develop the Phase 5.3 Bay Watershed Model, 30-meter land use coverage are the following:

- USGS Chesapeake Bay Land Cover 1984, 1992, 2001 and 2006 Data Series (CBLCD).
- County level agricultural census data (USDA 1982, 1987, 1992, 1997, 2002, 2007).
- 2001 Impervious Surface Land Cover data developed by the University of Maryland's Regional Earth Science Applications Center (RESAC) (Goetz et al. 2004).
- Ancillary data from the jurisdictions were used to develop the extractive land use cover, including spatial and tabular permitting information.
- Construction land use is a percentage of impervious change.

Table 5-2 provides a summary of the land use types modeled by the Phase 5.3 Bay Watershed Model, the specific land uses and a basic description of their derivation. Additional detail is available in Section 4 of the Phase 5.3 Chesapeake Bay Watershed Model report (USEPA 2010j) at http://www.chesapeakebay.net/model_phase5.aspx?menuitem=26169.

Table 5-2. Phase 5.3 Chesapeake Bay Watershed Model land uses

Land use type	Land use	Description	Source
Agricultural	Pasture	Based on pastureland areas from the agricultural census	USDA Agricultural Census
	Degraded riparian pasture	Unfenced riparian areas where livestock have stream access; represents a portion of the pasture use	A unique area designated by each state as the acres of planned riparian pasture fencing in their Tributary Strategies
	Nutrient management pasture	Pasture that is part of a farm plan where crop nutrient management is practiced. Nutrient management pasture is pasture that receives manures that are excess on a farm after all crop nutrient needs are satisfied.	Derived from the pasture land use and state nutrient management BMP tracking data

Land use type	Land use	Description	Source
	Alfalfa hay	Alfalfa is a separate hay category because it is a nitrogen-fixing, leguminous crop and receives different nutrient applications than other hay crops	USDA Agricultural Census
	Hay-unfertilized	(Wild hay) + (cropland idle) + (cropland in cultivated summer fallow)	USDA Agricultural Census
	Hay-fertilized	(Hay-alfalfa, other tame, small grain, wild grass, silage, green chop, act) – (wild hay) – (alfalfa) + (cropland on which all crops failed)	USDA Agricultural Census
	Conventional tillage with manure	Wheat, barley, buckwheat, sunflower, corn, sorghum, soybeans and dry beans	USDA Agricultural Census
	Conservation tillage with manure	Wheat, barley, buckwheat, sunflower, corn, sorghum, soybeans and dry beans	USDA Agricultural Census
	Conventional tillage without manure	(Cotton) + (tobacco) + (land used for vegetables) + (potatoes, excluding sweet potatoes) + (sweet potatoes) + (berries) + (nursery acres in the open) + (land in orchards)	USDA Agricultural Census
	Conservation tillage without manure	Crops typically grown for direct human consumption (such as cotton, tobacco, vegetables, potatoes and berries) and field nurseries	USDA Agricultural Census
	Nursery	Container nurseries, which typically have a high density of plants (10–100 plants per square meter) and high rates of nutrient applications	USDA Agricultural Census
	Animal Feeding Operations	Percentage of pastureland, based on animal populations from the agricultural census	Derived from the USDA Agricultural Census count of farms and the type and numbers of animals
Woodland	Forest, woodlots, and wooded	Includes woodlands, woodlots, wetlands and usually any wooded area of 30 meters by 30 meters remotely sensed by spectral analysis. Predominant land use in watershed.	Largely derived from the land area the was not developed, not in the Agricultural Census and not water of lakes and rivers
	Harvested forest	Estimated at 1% of forest, woodlots, and wooded land use	Derived from the forest, woodlots, and wooded land use
Developed	High-density pervious	High-Intensity Pervious Developed (Hp) lands are immediately adjacent to High-Intensity Impervious Developed lands and include mostly small	Derived from satellite data and density of road network

Land use type	Land use	Description	Source
		landscaped areas and lands adjacent to developed structures and major roadways. No portions of these lands are impervious	
	High-density impervious	High-Intensity Impervious Developed (Hi) lands contain more than 50% impervious surfaces per quarter-acre (on average) and generally represent impervious surfaces associated with large structures and major roads and include mostly commercial, industrial, and high-density residential land uses, interstates, and other major roads.	Derived from satellite data and density of road network
	Low-density pervious	Low Intensity Pervious Developed (Lp) lands are generally associated with Low-Intensity Impervious Developed lands and include residential lawns, golf courses, cemeteries, ball fields, developed parks, and other developed open spaces. Any impervious surfaces associated with these land uses are captured in either the low-intensity or high-intensity impervious developed classes depending on the size of the structure or road.	Derived from satellite data and density of road network
	Low-density impervious	Low-Intensity Impervious Developed (Li) lands contain less than 50% impervious surfaces per quarter-acre (on average) and generally represent impervious surfaces associated with small structures and minor roads and include mostly low to medium density residential areas and some sidewalks and driveways.	Derived from satellite data and density of road network
	MS4	Developed land coincident with an area requiring Municipal Separate Storm Sewer System (MS4) permits.	Derived from state regulatory data
Minor Land uses	Bare-construction	Based on the difference between the RESAC impervious land estimates of 1990 and 2000. Impervious land, which increased over the 10-year period, was assumed to have transitioned from a bare-construction land use	Derived from a combination of impervious area and construction permits

Land use type	Land use	Description	Source
	Extractive-Active and Abandoned Mines	Mines, gravel pits and areas affected by mine-related activities. In Virginia, acres are based on permit information; all others are based on RESAC data	State permitting data
	Open Water	Nontidal waters, acreage constant throughout model period	Satellite-derived estimate

Source: USEPA 2010j

Agricultural Land Uses

Satellite-derived estimates of cropland and pasture have higher uncertainty in the prediction of the extent of these land cover classes compared to the Census of Agriculture in certain land-river segments, so census data were used to inform and modify the extent of these land uses. County-level total agricultural land use from the agricultural census data were interpolated to the base years of 1990 and 2000. Agricultural land use was distributed to the model segments by the ratio of census agricultural classes for each county, and other land uses were distributed in the remaining model segment area in proportion to their acreage in the county. Annual changes in land use were linearly extrapolated or interpolated from the 1990 and 2000 base years and years covered in the agricultural census (1982, 1987, 1992, 1997 and 2002), resulting in annual sub-county data sets of land use.

The total agricultural area was split into different agricultural land uses, by the average ratio of crops in the agricultural census. Crops were aggregated by similar surface cover characteristics and fertilizer application rates to yield categories with similar nutrient-loading properties.

State agricultural engineers provided fertilizer and manure application timing and rates, crop rotation information, and field operation timing information. Manure application is represented in a time-varying mass balance of manure nutrients, according to animal population and predominant manure handling practices (USEPA 2010j).

Animal waste areas are defined by manure acres, which allows for the simulation of high nutrient content runoff and are based on the population of different animal types. The manure acres in a given area change based on the number of animals of each type (beef and dairy cattle, swine, laying hens, broilers and turkeys) and the implementation of animal waste management systems. Nutrient export is simulated as a concentration applied to the runoff from the manure acres (USEPA 2010j).

Urban Land Uses

For urban land representation, high- and low-density development and the proportion of impervious and pervious area were mapped for 1990 and 2000 (USEPA 2010j).

Other Land Uses

Other land uses represented in the model include construction, which typically has high sediment loading capacity; extractive-active and abandoned mines; and open nontidal water.

Future Land Use Estimations

The Chesapeake Bay Land Change Model was developed to help assess potential future changes in nutrient and sediment loads to the Bay resulting from land use changes (see Section 5.5 and Section 6).

5.8.3 Pollutant Source Representation

The Bay Watershed Model represents various sources of nutrients and sediments on the basis of the characteristics of the source and information available for characterizing the source. Point sources such as permitted wastewater and industrial dischargers that generally discharge continuously are represented directly in the model using locational data, flow, and discharge characteristics. Other sources, such as septic systems or agricultural activities, are represented in the model through the underlying land use coverage and assumptions related to nutrient and sediment production from associated land uses. Those sources can be thought of as land use-related sources because the simulation of their loading characteristics is driven by the land use categories with which they are associated. Several such land use-related sources are subject to NPDES permits. An example of such a land use-related source is an MS4 area, which is subject to an NPDES permit and must receive a WLA in the TMDL, but loadings are derived as a function of the modeled land use loading rates for associated land uses (e.g., urban pervious land). The following paragraphs summarize Bay Watershed Model representation of the major sources of nutrients and sediment to the Bay. Additional minor land use sources are also detailed in the Phase 5.3 Chesapeake Bay Watershed Model Report (USEPA 2010j).

Municipal and Industrial Discharges

Municipal and industrial discharges are considered direct inputs to the river reaches. In the Bay Watershed Model, the river segments are simulated as a completely mixed reactor, and all the wastewater discharged loads within a reach are summed for each of the river segments and input as a daily load (USEPA 2010j).

CAFOs

CAFOs are represented in the model as part of the AFO land use, which represents the production area of livestock operations. The loading is calculated on the basis of animal counts; manure nutrients production rate modified by feed considerations; time spent in pasture out of the production area; volatilization factors; and loss coefficients, which are dependent on storage facility type. The full description of the CAFO and AFO land use loads is available in the Scenario Builder documentation (USEPA 2010c) at http://www.chesapeakebay.net/modeling.aspx?menuitem=19303.

CSOs

CSO loads are not directly simulated by the Bay Watershed Model. CSO loads for the TMDL were developed using estimations of daily CSO flows and nutrient concentrations for the CSO communities in the watershed. For details related to how the loads were calculated, see Section 7 of the Phase 5.3 Chesapeake Bay Watershed Model Report (USEPA 2010j) at http://www.chesapeakebay.net/model_phase5.aspx?menuitem=26169.

MS4s

The estimated MS4 areas were provided by each of the jurisdictions and represent the current understanding of MS4 areas. While the best and final definition of an MS4 is delineated sewersheds (drainage area served by a sewer system), most jurisdictions could provide only municipal boundaries as an estimated MS4 area. There might be additional developed land, however, outside the municipal boundaries that also drains to the MS4 area, that can be shown by GIS data. The Phase 5.3 Bay Watershed Model uses the GIS data and topographic information to delineate the sewershed, which includes all land in the municipal boundaries and developed land outside the municipal boundaries that drains to the MS4 (USEPA 2010j).

Septic Loads

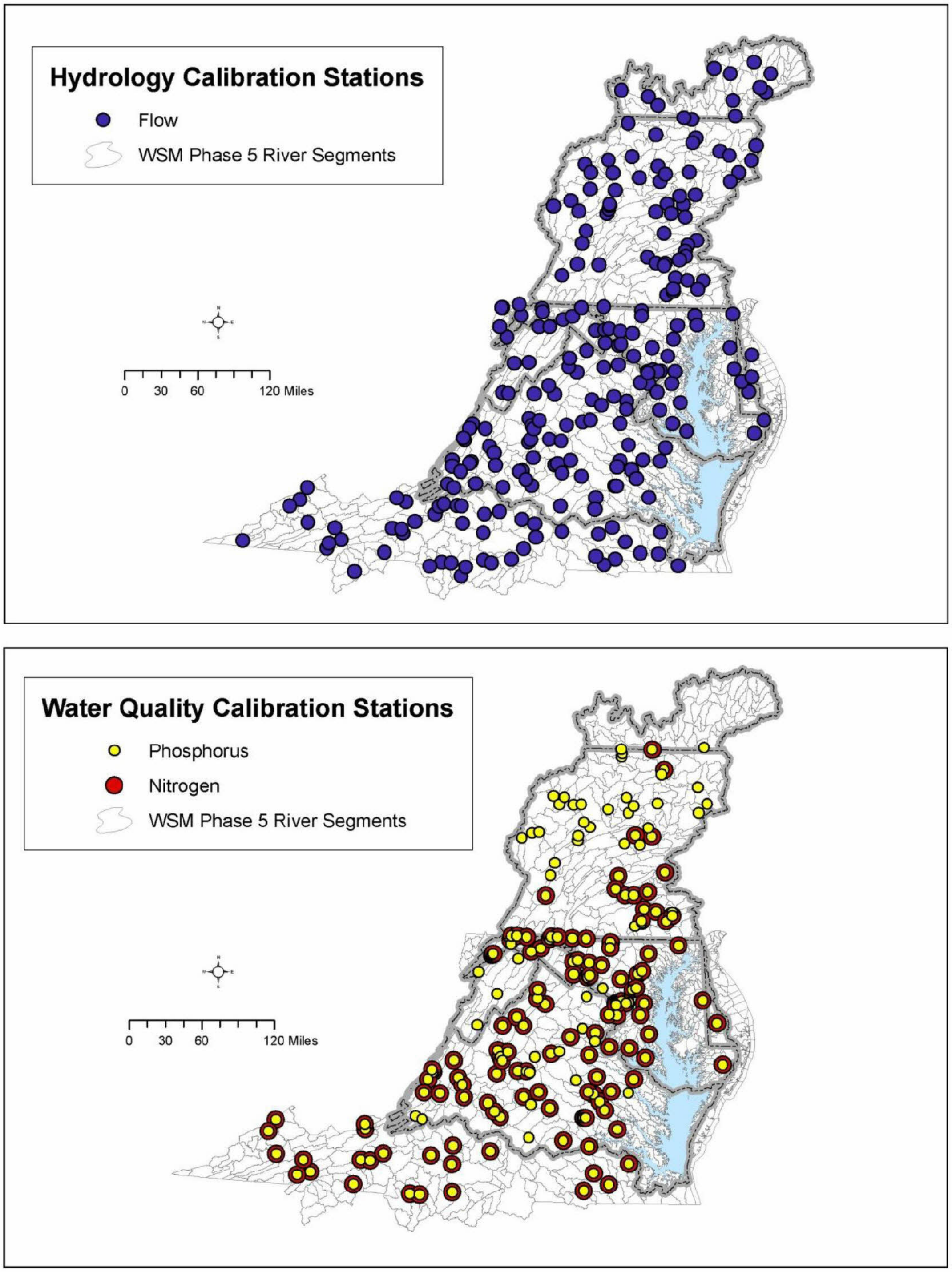
Septic system loads are calculated on the basis of U.S. Census Bureau estimates of the number of systems in the watershed and standard assumptions regarding nitrogen waste generation and attenuation. The model simulates nitrate discharges directly to stream and river reaches (USEPA 2010j).

5.8.4 Calibration

The Phase 5.3 Bay Watershed Model segments are defined such that segment outlets are in proximity to in-stream flow gauging and water quality monitoring stations to increase the accuracy of model calibration. Calibration involved comparing available streamflow and water quality data for the years 1985 to 2005 to watershed model calibration output for the same period.

To calibrate the model output, various water quality parameters such as simulated streamflows, (sediment) TSS, total phosphorus, organic and particulate phosphorus, phosphate, total nitrogen, nitrate, total ammonia, organic nitrogen concentrations and loads, temperature, and DO were compared to the observed data from the in-stream monitoring sites (Figure 5-14). In an automated calibration process, model parameters were adjusted to optimize the representation of observed in-stream conditions (USEPA 2010j).

The calibrated Bay Watershed Model was run for a 21-year hydrologic period (1985–2005) to simulate loads for various evaluation scenarios. Those loads were linked to the Bay Water Quality/Sediment Transport Model to test whether a given scenario met the Bay jurisdictions' WQS in the Bay. Modeled loads are reported as the average annual load over the modeled period.



Source: USEPA 2010i.

Figure 5-14. Phase 5.3 Chesapeake Bay Watershed Model hydrology (upper panel) and water quality (lower panel) monitoring calibration stations overlaid on the Phase 5.3 river segments.

5.9 Chesapeake Bay Water Quality and Sediment Transport Model

The Bay Watershed Model was linked to the Chesapeake Bay Water Quality/Sediment Transport Model (Bay Water Quality Model), which in turn was used to evaluate the impacts on Bay water quality conditions in response to changes in nutrient and sediment loading levels.

The Bay Water Quality Model combines a three-dimensional hydrologic transport model (CH3D) with a eutrophication model (CE-QUAL-ICM) to predict water quality conditions in the Bay resulting from changes in loads from the contributing area (Figure 5-15). The hydrodynamic model computes intra-tidal transport using a three-dimensional grid framework of 57,000 cells (Cerco, 2010 [in preparation]). The sediment transport model computes continuous three-dimensional velocities, surface elevation, vertical viscosity and diffusivity, temperature, salinity, and density using time increments of 5 minutes.

The eutrophication (water quality) model computes algal biomass, nutrient cycling, and DO, as well as numerous additional constituents and processes using a 15-minute time step ((Cerco and Noel, 2004)). In addition, the eutrophication model incorporates a predictive sediment diagenesis[12] component, which simulates the chemical and biological processes undergone at the sediment-water interface after sediments are deposited (Di Toro, 2001; Cerco and Cole, 1994).

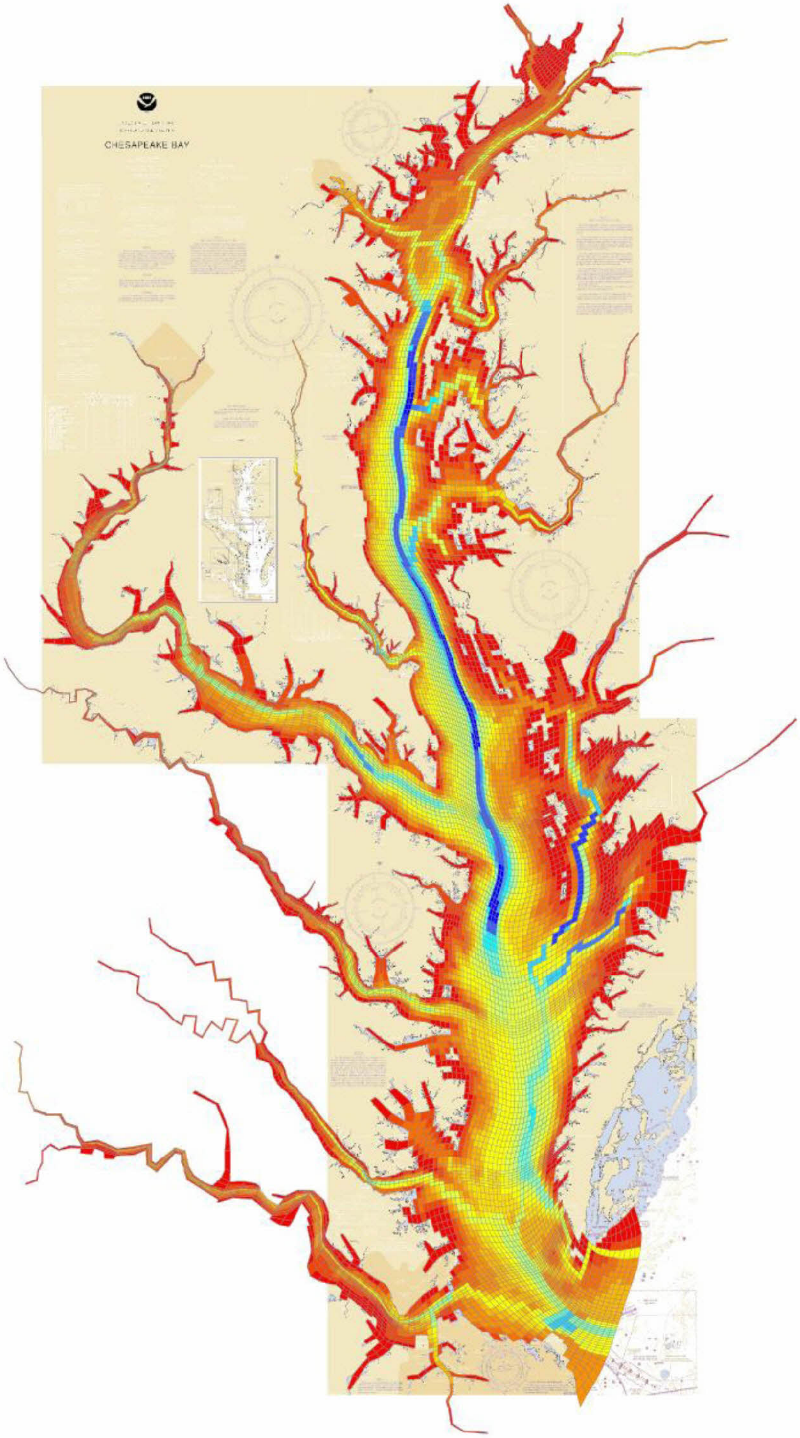
The hydrodynamic model was calibrated for the period 1991–2000 and verified against the large amount of observed tidal elevations, currents, and densities available for the Bay.

Computed flows, surface elevations, and vertical diffusivities from the hydrodynamic model were output at 2-hour intervals for use in the water quality model. Boundary conditions were specified at all river inflows, lateral flows, and at the mouth of the Bay.

Loads to the system include distributed or nonpoint source loads, point source loads, atmospheric loads, bank loads, and wetlands loads. Nonpoint source loads enter the tidal system at tributary fall lines and as runoff below the fall lines. Point source loads are from industries and municipal wastewater treatment plants. Atmospheric loads are deposited directly to the Bay tidal surface waters. Atmospheric loads to the watershed are incorporated in the distributed loads. Bank loads originate with shoreline erosion. Wetland loads are materials created in and exported from wetlands and include exported wetland oxygen demand.

Detailed documentation on the Chesapeake Bay Water Quality/Sediment Transport Model is at http://www.chesapeakebay.net/content/publications/cbp_26167.pdf.

[12] Predictive sediment diagenesis is a predictive model of how organic material and nutrients in sediment on the Bay floor are processed.



Source: Cerco, 2010 [in preparation].

Figure 5-15. The detailed 57,000 cell grid of the Chesapeake Bay Water Quality and Sediment Transport Model.

5.9.1 Nonpoint Source Loads

Nonpoint source loads to the Bay Water Quality/Sediment Transport Model are from the Phase 5.3 Bay Watershed Model. Loads are provided daily, routed to surface cells on the model grid. Routing is based on local watershed characteristics and on drainage area contributing to the cell adjacent to the land (USEPA 2010j).

5.9.2 Point Source Loads

Wastewater discharged loads to the Bay model were based on reports provided by local regulatory agencies which, depending on the source, were specified annually or monthly. In the model, loads from individual sources were summed into loads to model surface cells and were provided monthly (USEPA 2010j).

5.9.3 Atmospheric Loads

The EPA CBP Office computed the daily atmospheric loads for each Water Quality and Sediment Transport Model surface cell (USEPA 2010j). Wet deposition loads of ammonium and nitrate were derived from National Atmospheric Deposition Program observations. Dry deposition load was derived from the CMAQ. Deposition loads of organic and inorganic phosphorus were specified on a uniform, constant, areal basis derived from published values.

5.9.4 Bank Loads

Bank loads are the solids, carbon, and nutrient loads contributed to the water column through shoreline erosion. Although erosion is episodic, bank loads can be estimated only as long-term averages by areal surveys. The volume of eroded material is commonly quantified from comparison of topographic maps or aerial photos separated by time scales of years. Consequently, the erosion estimates are averaged over periods of years, but bank loads are input into the Bay Water Quality/Sediment Transport Model as episodic events as determined by a wave energy submodel. Bank loads were estimated for shoreline and sub-tidal erosion for much of the Chesapeake Bay shoreline on a scale of about every 10 kilometers of shoreline.

5.9.5 Wetlands

Wetlands loads are the sources (or sinks) of oxygen and oxygen-demanding material, such as carbon, that is associated with wetlands that fringe the shore of the Bay and tributaries. These loads are invoked primarily as an aid in calibrating tidal tributary DO concentrations. Loads to each cell were computed by multiplying the amount of adjacent wetlands area by the amount of areal carbon export or oxygen consumption. A uniform carbon (C) export of 0.3 grams (g) C per meters^2 per day (m-2 d-1) was employed, leading to a uniform oxygen (O2) demand of 2 g O2 m-2 d-1. Segments receiving the largest carbon loads and subject to the greatest oxygen consumption include the mid-portion of the Bay, Tangier Sound, several Eastern Shore tributaries, the middle and lower James River, the tidal fresh York River, and the York River mouth.

5.9.6 Model Setup

Within the Bay Water Quality Model, 90 of the 92 Chesapeake Bay segments are fully represented within the 57,000 model cells and fully simulated. Two segments—the Western Branch Patuxent and the Chesapeake and Delaware Canal—were either not included in the modeled Chesapeake Bay segments or not fully simulated in the Bay Water Quality/Sediment Transport Model. Bay TMDLs were developed for both of these tidal segments using information from the Phase 5.3 Bay Watershed Model, Bay Water Quality Model results from adjoining tidal Bay segments, and other documented sources (see Section 9).

The Western Branch Patuxent River (WBRTF) segment in Maryland (see Table 2-1 and Figure 2-5) was not simulated in the Bay Water Quality/Sediment Transport Model because of the lack of quality data on the tidal river's bathymetry (Cerco, 2010 [in preparation]). In June 2000, the Maryland Department of Environment published a BOD TMDL for this tidal river segment to address DO impairments (MDE 2000). Therefore, WBRTF is listed on Category 4a for a BOD TMDL on Maryland's 2008 Integrated Report (see Table 2-1) (MDE 2008). A TMDL for segment WBRTF has been developed on the basis of (1) Maryland Department of Environment's original BOD TMDL and loading information from the surrounding Phase 5.3 watershed model segments that drain directly into the Western Branch Patuxent River segment, and (2) outputs from the *down-tide* Patuxent River segments (PAXTF, PAXOH, PAXMH), which are also listed as impaired (see Table 2-1) (MDE 2008).

The Delaware portion of the Chesapeake and Delaware Canal (C&DOH_DE) is simulated in the Bay Water Quality Model as a boundary condition[13] for the Delaware Bay using constant flow and load (Cerco, 2010 [in preparation]). The segment is listed as impaired (see Table 2-1) (DE DNREC 2008). A Chesapeake Bay TMDL for segment C&DOH_DE was developed using a combination of loading information from the surrounding Phase 5.3 Bay Watershed Model segments that drain directly into this Bay segment and outputs from the down-tide Chesapeake Bay segments (C&DOH_MD, ELKOH, and CB1TF), which also are listed as impaired (see Table 2-1 and Section 9) (MDE 2008).

5.10 CHESAPEAKE BAY CRITERIA ASSESSMENT PROGRAM

Output from the Bay Water Quality Model is used to modify historical water quality monitoring observations from the period 1991–2000 for the purposes of determining Chesapeake Bay WQS attainment under various pollutant load reduction scenarios (for more details on this process, see Section 6.2.1). To perform the necessary procedures on the large amount of data required from both the Bay Water Quality Model and the Chesapeake Bay Water Quality Monitoring Program database, a set of Fortran modules were developed. These post-processing modules read output from the Bay Water Quality Model (hourly values for DO; daily values for chlorophyll *a*), perform regression analyses, and apply those regressions to the appropriate historical monitoring data set. Additional Fortran modules then perform the same standardized, automated criteria assessment procedures that are used to assess more recent monitoring data for the Bay jurisdictions' section 303(d) listing reports.

The source code for this suite of Fortran modules is maintained by the EPA CBP Office's Modeling and Monitoring teams on behalf of the partnership, and are at ftp://ftp.chesapeakebay.net/Monitoring/CriteriaAssessment/.

The process by which historical monitoring data are *scenario-modified* using output from the Bay Water Quality Model is summarized in Section 6.2.1. For a detailed description of the

[13] Boundary conditions refer to the definition or statement of conditions or phenomena at the boundaries of a model; water levels, flows, and concentrations that are specified at the boundaries of the area being modeled.

Chesapeake Bay water quality criteria assessment procedures used for generating 303(d) listings, see EPA's 2008 *Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll a for the Chesapeake Bay and Its Tidal Tributaries–2008 Technical Support for Criteria Assessment Protocols Addendum* (USEPA 2008a) and EPA's 2010 *Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll a for the Chesapeake Bay and Its Tidal Tributaries: 2010 Technical Support for Criteria Assessment Protocols Addendum* (USEPA 2010a).

5.11 CLIMATE CHANGE SIMULATION

The potential effects of climate change have not been explicitly accounted for in the current Bay TMDL allocations beyond application of a 10-year hydrologic period because of staff resource and time constraints and known limitations in the current suite of Bay models to fully simulate the effects of climate change. A preliminary assessment of climate change impacts on the Chesapeake Bay was conducted, in parallel, using an earlier version of the Phase 5 Bay Watershed Model and tools developed for EPA's BASINS 4 system including the Climate Assessment Tool. Flows and associated nutrient and sediment loads were assessed in all river basins of the Chesapeake Bay with three key climate change scenarios reflecting the range of potential changes in temperature and precipitation in the year 2030. The three key scenarios came from a larger set of 42 climate change scenarios that were evaluated from 7 Global Climate Models, 2 scenarios from the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios storylines, and 3 assumptions about precipitation intensity in the largest events. The 42 climate change scenarios were run on the Phase 5 Watershed Model of the Monocacy River watershed, a subbasin of the Potomac in the Piedmont region, using a 2030 estimated land use based on a sophisticated land use model containing socioeconomic estimates of development throughout the watershed. The results provide an indication of likely precipitation and flow patterns under future potential climate conditions (Linker et al. 2007, 2008) (see Appendix E).